Modeling an Automobile Steering System Using Axiomatic Design's Design Matrix and the Design Structure Matrix

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ABSTRACT

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By Matthew R. Bagley

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The automobile steering system can be thought of as a system within a system. The steering system has clear functions and requirements as well as many interrelated components and subsystems including the front tires, wheels, front suspension, steering gear, intermediate shaft, column and steering wheel. System decomposition is an important aspect of this system analysis.

The scope of this thesis is the steering system and steering attributes of a particular new model program code named UXXX. An important element of this research is a case study where an error state called Nibble was discovered late in the program. The attempted resolution of the concern caused much turmoil and drove higher component costs, engineering costs, launch delays, warranty costs and decreased customer satisfaction.

The main objective of this work was to execute good system analysis to understand key interactions within the system and to provide documentation and knowledge transfer of key discoveries.

A requirement based Design Structure Matrix (DSM) was used as the primary methodology for system analysis. In order to construct the DSMs, Axiomatic Design's Design Matrix (DM) was used to develop Functional Requirements (FRs) and Design Parameters (DPs). The requirements based DSM was derived from the DM.

DSMs were created from requirements based interactions, spatial interactions and Nibble relationships (Design Parameters influencing Nibble). Herein outlines an approach for synthesizing functional requirements to create a quality Design Matrix and then transform into a DSM. One key discovery is in the development of FRs using a left-to-right and then a right-to-left approach followed by synthesis. Another important development is a matrix comparison method where matrices of different types of interactions are compared through matrix addition. Discussion of key questions from the case are presented as well as conclusions, recommendations and proposed future work.

ACKNOWLEDGEMENTS

I wish to acknowledge and thank Daniel E. Whitney for advice and direction regarding this research. His feedback and willingness to discuss various topics throughout the process of writing this thesis was very valuable and much appreciated.

I would also like to acknowledge and thank Qi Hommes for her willingness to share her expertise and to provide guidance in applying the methods contained herein. She took time away from her busy schedule to work with me and provide much needed help.

I thank Ford Motor Company for providing me the opportunity to continue my education at one of the finest learning institutions that exist. I thank my many co-workers for their input, support and encouragement during these past two years.

Most importantly, I thank my wife Maria. Without her all of this would have been impossible. She encouraged me through these past two years, never complained about my absence and always provided her love and confidence. The responsibility of caring for our home and family (four children) while I was away was not easy. I love her and appreciate her for what she has done and is doing.

Matt Bagley

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1.0 INTRODUCTION

Let me begin this thesis by briefly discussing the motivation behind my desire to study Systems Engineering and product development. It begins with my interest and passion for consumer products. I enjoy consumer products and their impact on the world around us. It began for me when I was about twelve years old. At that time I was very motivated by skiing in the Rocky Mountains. One of my challenges was paying for lift tickets throughout the season. Also at that time, the Sony Walkman was very popular. I reasoned with myself that skiing and listening to music on the portable cassette tape player could go hand in hand. I had seen a unique product that allowed skiers to strap the Walkman to their chest while protecting it in a padded case. These were two great ideas that came together to answer the desires of the skier. I had a small Walkman style cassette player at the time, so I decided to fabricate a protective case for it. I purchased the materials I needed, made a pattern, pulled out my mother's sewing machine and produced the case. When I went skiing with friends, they saw the case I was using to carry my Walkman in and they wanted to know where I got it. When I told them I made it, they wanted one too. I produced and sold enough Walkman cases that year to pay for my entire season of skiing.

I continue to be interested in products and product development. Even more than the actual fabrication of the product, the process of identifying and satisfying needs of the consumer intrigues me. I enjoy seeing new products introduced that bring excitement and enhances lives in one way or another.

Understanding the wishes of the consumer is far more challenging than it seems. After all there are billions of potential customers and an infinite combination of needs and desires. Transforming the wishes of consumers to the planning and development of a product that, when produced, does in fact meet those wishes completely, is even more challenging.

In the automobile industry, competition has become so fierce that some manufacturers have employed huge incentives to maintain market share at the expense of profitability. Domestic automobile manufacturers are averaging significantly higher incentives than their Japanese counterparts. As an engineer at one of the domestic manufacturers, I am motivated to try to understand why there is such a difference. In my experience I have witnessed the turmoil caused in the months and weeks before a new vehicle program launch when targets change, leading to late design changes. I have seen the impact that just a few personalities and opinions can have on the success of a newly launched consumer product. In my experience, I've seen specifications and tolerances set at industry highs (e.g., best-in-class tire specifications and the tightest wheel tolerances in the industry) with low resulting performance (e.g., vehicle vibration warranty claims). Not only do tighter tolerances cost more, lower performance is the result. In addition, customer data shows that in the case of one particular domestic SUV (to be discussed later), attributes executed at high levels were not appreciated or valued by consumers. These certain attributes were delivered at the expense of other attributes considered more important to the customer. Products that don't deliver what the customer wants and delivers in areas they don't value, is wasteful.

The challenges discussed so far and my interest in products and product development, have motivated me to study Systems Engineering. I believe that good Systems Engineering is in part a solution to many of the issues discussed above. As further introduction to this thesis, the following items will be discussed further:

- Systems – defined
- What is Systems Engineering?
- Systems Engineering at Ford Motor Company

1.1 Systems – Defined

"A system is a network of interdependent components that work together to try to accomplish the aim of the system. A system must have an aim. Without an aim, there is no system." Edward Demming

1.1.1 The World is a System

Systems are all around us. The world we live is one very large, complex system with a network of interdependent elements or components. The world can be thought of as a system where the elements are land, water and atmosphere. It can be thought of as a system with elements that include nationalities of the peoples of the earth. The world can be thought of as a system where the elements or components of the system are the continents, countries and territories. The elements of the world system can be organizational. The people of the earth have developed various political systems and interact and interrelate with each other.

The discussion of the world as a system gives understanding that systems can be described in many ways. The way in which a system is described depends on the motivation and purpose for studying the system. Those studying the earth as a system may have very different motivations including increased understanding of politics, geography, ecology, anthropology, meteorology, economics, sociology, etc. Those studying astronomy would label the earth itself, as large and complex as it is, as a single element or component of an even larger system we call the solar system.

So, if according to Demming, the definition of a system is the interrelation of elements of components that work together to accomplish the aim of the system, what is the aim of the system we call earth? This is merely a rhetorical question not to be discussed within the scope of this thesis but to point out that all systems, large or small, complex or simple, have an aim. The aim of a system will be described here after as the function or purpose.

Definition (Random House Dictionary of the English Language. 2nd ed. New York: Random House, Inc. 1994)

System: an assemblage or combination of elements or parts forming a complex or unitary whole, such as a river system or a transportation system; any assemblage or set of correlated members, such as a system of currency; an ordered and comprehensive assemblage of facts, principles, or doctrines in a particular field of knowledge or thought, such as a system of philosophy; a coordinated body of methods or a complex scheme or plan of procedure, such as a system of organization and management; any regular or special method of plan of procedure, such as a system of marking, numbering or measuring (Blanchard, et al). Systems are physical and non-physical, human made or non-human made. In the context of this thesis, a system is a human made assembly of physical elements or components, engineered to interact and interrelate in a way that accomplishes a desired functional output. This functional output is the aim of the engineering system.

Blanchard and Fabrycky state that an engineering system contains three key elements; components, attributes, relationships.

1. Comp*onents* are the operating parts of a system consisting of input, process, and output. Each system component may assume a variety of values to describe a system state as set by some action and one or more restrictions.
2. *Attributes* are the properties or discernible manifestations of the components of a system. These attributes characterize the system.
3. *Relationships* are the links between components and attributes.

Not all attributes by this definition are desirable. Attributes can be divided into both attributes and error states. Error states are the undesirable outputs of the interactions within a system. Error states are the unplanned result of interactions that often lead to undesirable outputs of the engineering system.

1.1.2 Principles of a System

From Ford training document on Systems Engineering Fundamentals:

- A system has a function, purpose, and objective.
- A system is more than the sum of its parts.
- A system is no better than its weakest element.
- Optimizing the elements usually will not optimize the whole.
- Interactions among components often determine the performance of a system.
- Components of a system contribute to the behavior of the system and are changed by being part of the system

1.1.3 Systems Within Systems

Engineering systems are often large and complex. The earth was presented earlier as a system within a system. The earth as a whole can be thought of as a system in many ways but at the same time, the earth is a component or element of a much larger system. In the same way the automobile can be thought of as a system within a system. The automobile is a single element of the transportation system. At the same time, the automobile is a system in and of itself. The automobile has components, attributes and relationships. The automobile can be divided into smaller, less complex systems such as body, chassis, power train, climate control, etc. Each of these systems is a system within a system.

The automobile is both physical and human-made. The human-made aspect of developing an automobile is the subject of the next section where systems engineering is discussed in further detail.

1.2 What is Systems Engineering?

There is no single definition of Systems Engineering. Blanchard and Fabrycky cite many definitions and combine the salient elements into the following areas of emphasis:

1. A top-down approach that views the system as a whole.
2. A life-cycle orientation that addresses all phases to include system design and development, production and/or construction, distribution, operation, maintenance and support, retirement, phase-out, and disposal.
3. A better and more complete effort is required regarding the initial definition of system requirements, relating these requirements to specific design criteria and the follow-on analysis effort to ensure the effectiveness of early decision making in the design process.
4. An interdisciplinary or team approach throughout the system design and development process to ensure that all design objectives are addressed in an effective and efficient manner (Blanchard, et al.).

As mentioned, systems engineering is a top-down engineering approach to the system design process. Simply put, the systems engineer begins the design process by identifying customer requirements and translating them into system level engineering requirements. System level requirements are cascaded to subsystem requirements and then to component level requirements. Systems engineering strives to meet the customer requirements through the execution and verification of requirements at all levels of the system. Systems engineering is interdisciplinary where boundaries between functions are less important than the interactions within the system. The process followed to design and develop systems is the product development process (PDP). Systems Engineering contrasts from conventional engineering in that component design is driven by system requirements. Figure 1 illustrates that the component view typically focuses on designing each component without considering overall functionality of the next higher system or subsystem. The Systems Engineering View on the other hand is driven by functional requirements.

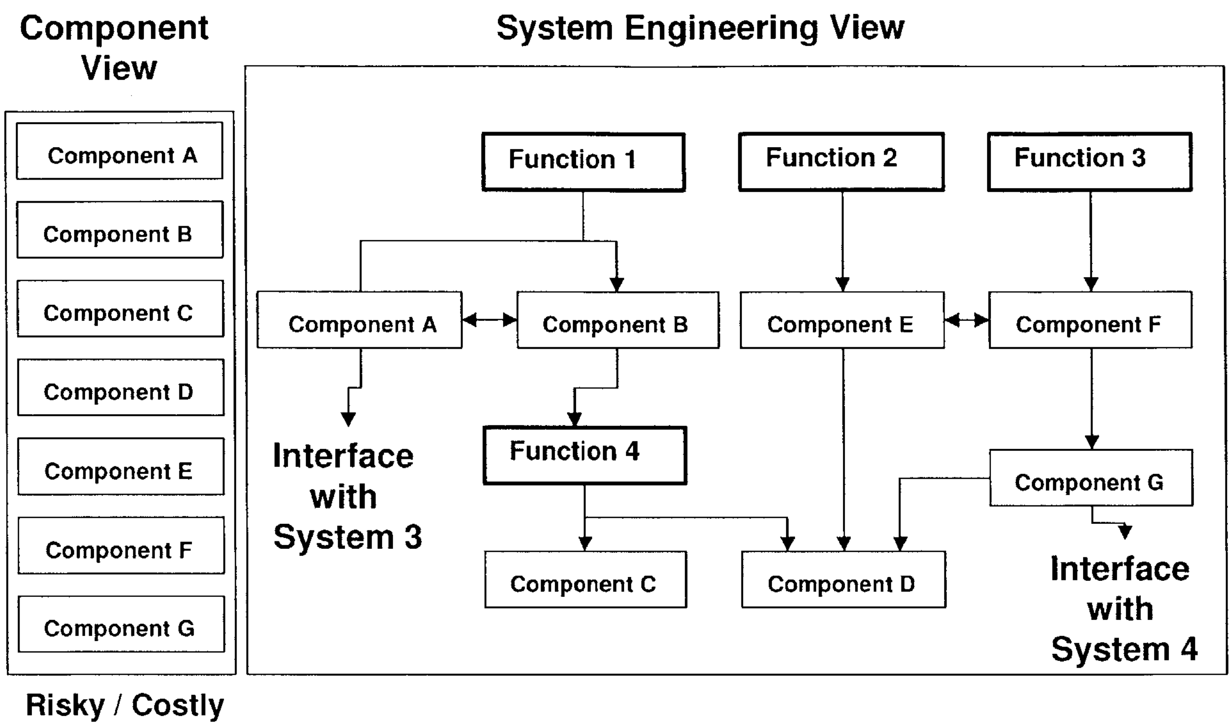


Figure 1: Component View vs. System Engineering View (Ford SEF)

A Ford Motor Company training course on Systems Engineering fundamentals outlines key principles of systems engineering as:

- A customer requirements driven engineering and management process
- Transforms the voice of the customer into a feasible and verifiable product/process of appropriate configuration, capability and cost.
- Integrates total engineering effort to meet cost, schedule and performance objectives
- Is both a technical and a management process
- Requires diverse perspectives

1.3 Product Development Process

The product development process will be discussed later in more detail. It is important to point out that the product development process and systems engineering essentially refer to the same process. The systems engineering process is the product development process in the context of this thesis. There are many approaches to product development. The selection of an approach or methodology for product development depends on the type, size and scope or complexity of the product being developed.

In a generic sense, the product development process consists of the following phases (Ulrich and Eppinger):

Phase 0 – Planning

Phase 1 – Concept Development

Phase 2 – System-Level Design

Phase 3 – Detail Design

Phase 4 – Testing and Refinement

Phase 5 – Production Ramp-up

In addition to the phases discussed by Ulrich and Eppinger, the product development process must include the full life cycle of the system through operational use and retirement (Blanchard, et al.).

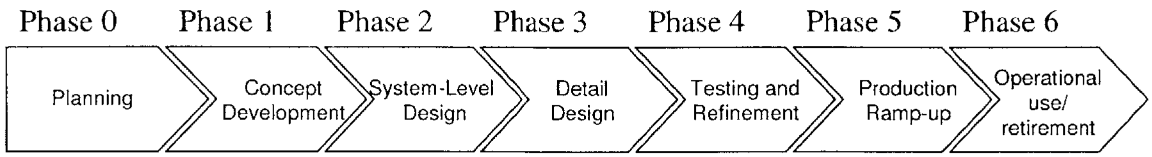


Figure 2: Generic Product Development Process

1.4 Systems Engineering at Ford Motor Company

1.4.1 Brief History of Ford Motor Company

Ford Motor Company was founded in on June 16th, 1903. Founder, Henry Ford, is remembered in American history as the inventor of moving assembly line and one of the forces that shaped the Industrial Age. Soon after starting Ford Motor Company, "Henry Ford and his engineers feverishly went through nineteen letters of the alphabet—from Model A to Model S—selling 20,000 cars between 1903 and 1908. While other automakers put their shoulders behind building automobiles for the rich, Henry sought to create a utilitarian car, "large enough for the family but small enough to run and care for," he said. "It will be so low in price that no man making a good salary will be unable to own one."

"In early 1907, he set up a special workroom at the company's new plant... to work on his "universal car," as he called it. On October 1, 1908, the Model T—Henry's motorcar for the great multitude—was ready for full production." The product development cycle of the Model T was just over a year and half and its lifecycle was nearly nineteen years selling 15 million. After the final Model T rolled off the assembly line, Ford closed all of its plants to retool for a different automobile. The public waited for six months to see what Ford would offer to follow the Model T. Toward the end of the Model T's life cycle, Ford's market share suffered seriously, falling from two thirds of all automobiles produced to just one-third in its last two years of its production. The New York Times wrote, "Henry Ford continues to be the greatest single influence in the motor world but his domination has sharply declined in the face of heavy competition."

The popularity of the Model T was based on low cost, durability of design, serviceability, and simplicity. Today, many of the same elements that allowed the Model T so much success are also important and competition is more heated than ever. The automobile industry has reduced in the number of competing companies but offer many more automobile alternatives to the consumer. Automobiles in modern times are much more complex than they were when Henry Ford developed the Model T. Automobiles contain complex electrical and mechanical systems controlled by computer software. Safety and reliability are critical to meeting customer requirements. The ability to develop the next car quickly enough and at the right price for the next change in the market is very challenging and critical for survival in the auto industry today. The life cycle of an automobile is no longer nineteen years without significant changes. Today Ford follows a systems engineering approach to develop automobiles called the Ford Product Development System (FPDS).

Systems Engineering at Ford Motor Company includes the following elements:

- Product Development Process - FPDS
- System Partitioning and Managing Interfaces
- Developing and Organizing Requirements
- Requirements Cascade
- Verification and Sign-off
- Engineering Disciplines

1.4.2 Product Development Process – FPDS

Ford's Product Development Process is the result of one hundred years of experience in developing and manufacturing automobiles. Benchmarking competitors and others outside the industry provided important input to FPDS. The intent of FPDS is to provide a disciplined, process oriented approach to systems engineering and to shorten the development time, improve quality and reduce the cost of development. FPDS is a combination of a phase-gate project management methodology and the System "V" product development methodology. FPDS is an engineering and management process for managing vehicle development program deliverables through key milestones throughout the concept, design, verification and launch process. Key milestones include; Program Kick-Off <KO>, Strategic Intent <SI>, Strategic Confirmation <SC>, Program Approval <PA>, Program Readiness <PR> and Launch <J1>.

A Systems Engineering training course at Ford Motor Company shows how the system "V" is combined with the project management process:

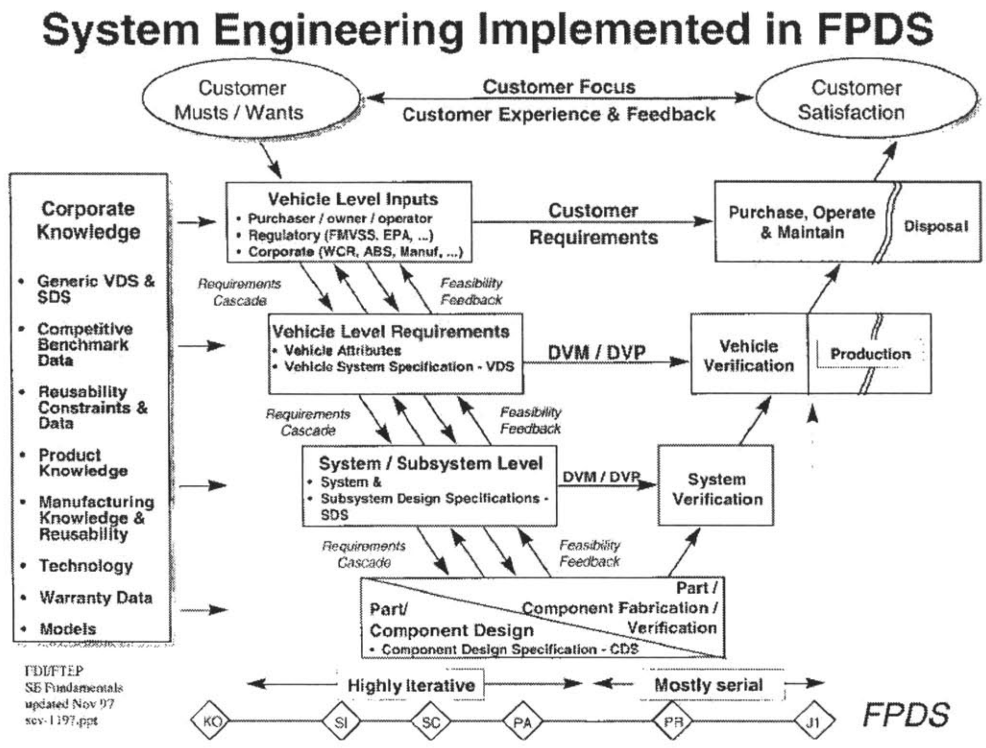


Figure 3: System Engineering Implemented in FPDS

Figure 4 below illustrates a high level overview of the Ford Product Development System (FPDS) front-end process.

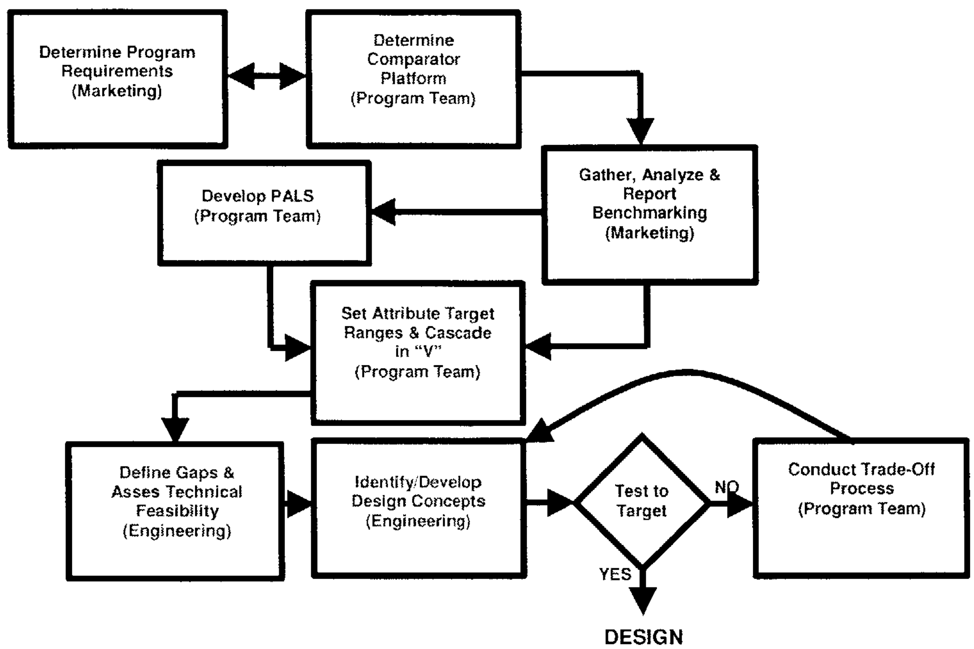


Figure 4: The Ford Product Development System

FPDS is designed for Marketing to recognize the need or want for a new product or derivative product in the marketplace. This need is passed on to a newly formed Program Development Team. The program team, with Marketing's input, decides which internal and competitive vehicles the new entry will be judged against. These are called the program comparator vehicles. Marketing is tasked with gathering the competitive benchmarking data and reporting back to the program team. With this data in hand the program team, together with Marketing, develops the general requirements of the vehicle.

1.4.3 System Partitioning and Managing Interfaces

Partitioning is the act of dividing a system in to meaningful and manageable subsystems based on spatial relationships or functional characteristics. Ford Motor Company typically partitions a vehicle by function. The following partitions represent the five key functional areas of the vehicle system:

- Body
- Electrical
- Powertrain
- Chassis
- Climate Control

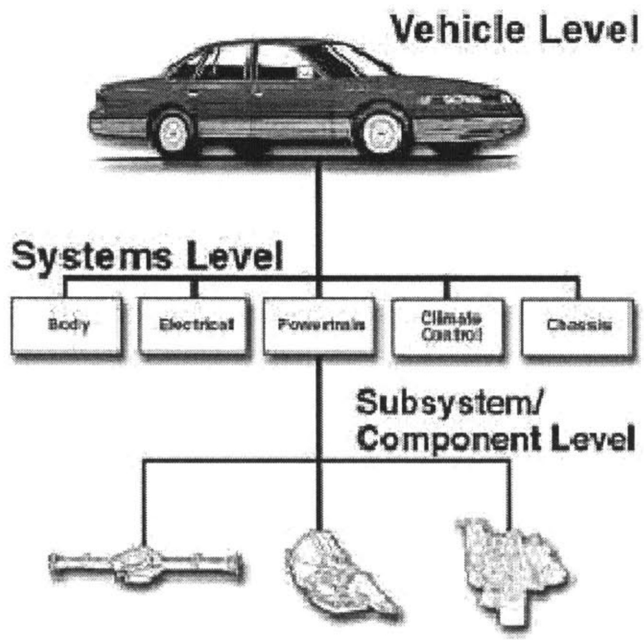


Figure 5: Vehicle Functional Partitions

In principle, product development at Ford Motor Company takes place within these functional partitions. The relationship of the functional partitions with each other are defined as interfaces. Effectively managing these interfaces is the essence of systems engineering.

1.4.4 Developing and Organizing Requirements

System level requirements or targets developed by the program team are organized in the Product Attribute Leadership Strategy (PALS) for the new program. This is the process that takes each customer requirement that is to be addressed by the new entry and positions it among competitor products. In principle, the program team determines targets for each vehicle attribute to be either, leader (L), among the leaders (A), competitive (C) or uncompetitive (U). This priority ranking of customer attributes drives the rest of the target setting process. When PALS is completed it is the responsibility of the program team to distill customer requirements into well-defined and measurable engineering statements called requirements.

The final agreed upon requirements are fed into a document called the "Vehicle Design Specification" (VDS). With the specifications set, the engineering teams begin development of designs to meet the requirements. Engineering develops a Design Verification Plan "DVP" that indicates which tests will be performed to verify design performance to target.

1.4.5 Requirements Cascade

The process of taking vehicle requirements, communicating them the system level where system level requirements are then developed and communicated to subsystem/component level where subsequent subsystem/ component requirements are developed is call requirements cascade. In principle, Ford Motor Company completes the requirements cascades in the familiar system "V".

Ford uses a targets process that includes a combination of Product Attribute Leadership Strategy (PALS), and standardized Vehicle Design Specifications (VDS) and System Design Specifications (SDS).

The Ford "Requirements Development and Flow-Down" process begins early in the product development timeline just after program kick-off. The goal of the Ford Product Development System (FPDS) Targets Process is to provide each program team with a consistent, structured process when setting, evaluating tradeoffs and verification methods. The FPDS Targets Process first obtains vehicle level targets that reflect the needs/ wants of the customer, corporation and government (regulatory). These requirements are translated into 15 corporate attributes (proprietary).

After requirements have been translated into the 15 corporate attributes, they are assigned a priority ranking by customer, corporate and regulatory inputs. This ranking process results in a brand profile matrix and is a key element of PALS. PALS considers product attributes grouped in several generic categories such as: Accessibility/Affordability, Vehicle Comfort, Vehicle Design, Driving Dynamics, Package, Etc.

Strategic targets are set for each product attribute as leader (L), among the leaders (A), competitive (C) or uncompetitive (U). Once the PALS target setting is complete, reviewed and approved it is subsequently cascaded to the vehicle product program team. Attributes and sub-attributes are used to organize design specifications for the vehicle as a whole as well as sub-systems. These design specifications are a standardized set of requirements with associated verification methods.

There are several methodologies for product development processes as mentioned previously, Ford Motor Company has determined the best fit for developing automobiles is a combination of the System "V" methodology and the phase-gate project management approach.

1.4.6 Verification and Sign-Off

By this stage in the product development process, requirements have been clearly developed, cascaded to appropriate design centers and designs of components, subsystems and systems achieved. Verification and sign-off begins at the confirmation prototype (<CP>) phase of FPDS and completes by Change Cutoff (<CC>). Verification that the requirements have been met is the reverse of cascading requirements to the component level (right hand side of the system "V"). Verification that components meet design requirements is followed by subsystem and system. Ultimately, the vehicle level requirements are verified and documented.

Documentation of verification and sign-off at the subsystem level is accomplished via the Design Verification Plan and Report (DVP&R).

1.4.7 Engineering Disciplines

Engineering disciplines are followed in order to design each component and subsystem to meet engineering requirements leading ultimately to final engineering sign-off based on the completion of the Design Verification Plan and Report (DVP&R).

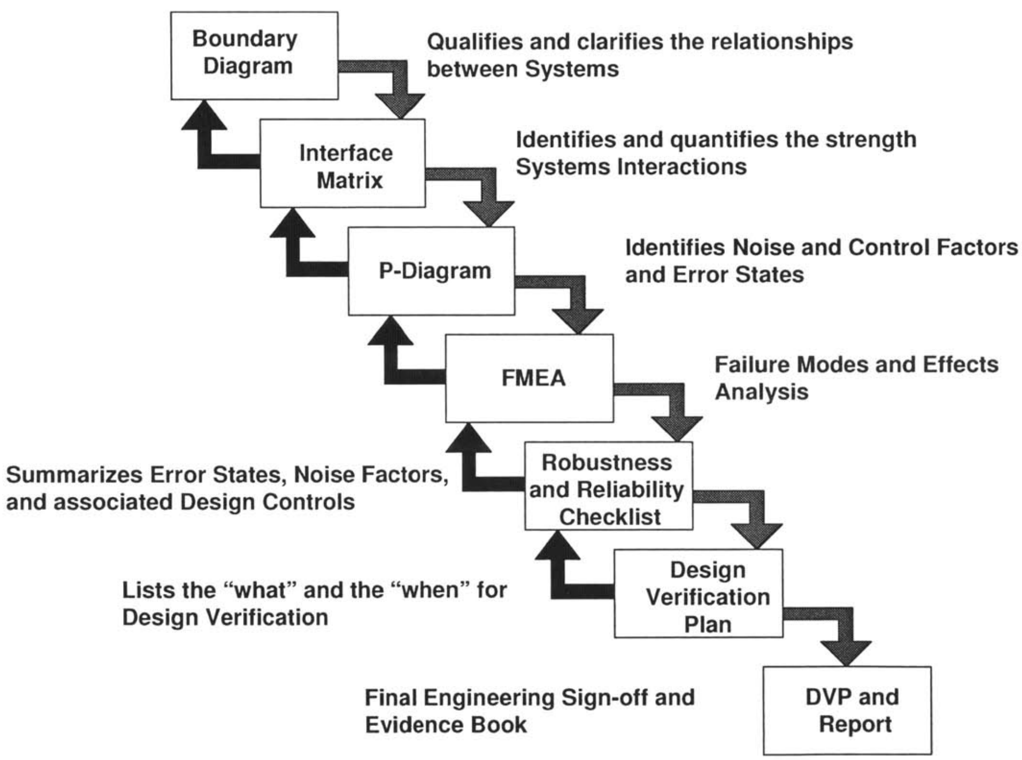


Figure 6: Ford Motor Company Engineering Disciplines

1.4.8 CAE in Product Development

At early stages in the program development CAE is used when available to get an early indication of design performance, otherwise physical prototypes are developed for testing.

Once initial test results (CAE or physical) are available the difficult trade-off process begins. If the initial tests indicate that the design is capable or close to meeting the target then product development continues. If testing shows a disconnect between design performance and the set target the program team must make the trade-off between iterating the design at the risk of program timing or revising the target at the risk of customer satisfaction. Revising the target would also mean re-visiting PALS to determine if the new target range changes the competitive placement of the new product with respect to the tested attribute. When the trade-off process is completed designs are finalized and full product verification begins. This is done in the second half of the "V" where designs are first verified at the component level and then moved up the "V" to verify sub-systems, systems and ultimately the complete vehicle.

1.4.8.1 CAE Process Flow

The analytical process has no fixed starting point in the FPDS. The most likely CAE formal process flow is shown below. CAE is the primary product development tool in FPDS; it is used with other tools and processes for:

1. Target Setting (Selection of Consistent Targets & System/Component Hardware)
2. Target Validation (Consistency between Targets: - Level to Level & Target to Target)
3. Design Experimentation (Alternative Designs that will meet the Targets)
4. Design Verification and Confirmation (The Design meets the Set of Targets)

5. System and Attribute Integration (Managing the Interfaces between Systems & Attributes)

Translated into FPDS process terms, these five areas of use will be found in all four work-breakdown categories of the FPDS process. The four work breakdown categories the main process has been structured into are:

1. Define Product & Process Requirements
2. Design Product & Process
3. Verify/Build/Produce Product & Process
4. Manage Program

In principle, it is through FPDS, the system "V" and other methods previously discussed that products are developed at Ford Motor Company. Execution of these methods resulting in flawless products is an increasing challenge as automobiles become more complex and as competition becomes more intense.

1.5 Background

In Chapter 3.0 of this thesis a detailed case study will be presented discussing an automobile error-state called "Nibble". Nibble, simply stated, is a rotational vibration at the steering wheel that occurs at highway speeds and is caused by vehicle sensitivity to tire and wheel force variation. Nibble is perceived by the driver as a vibration at the steering wheel when driving at highway speeds. A detailed description of Nibble will be presented in Chapter 2.0. Throughout this thesis Nibble will also be referred to as a steering system error-state.

Nibble is the result of natural frequencies in the steering system. These natural frequencies are the result of force variations, run-out and imbalance of the tire/wheel assembly and are a function of system characteristics such as mass and damping. Spatial interactions within the steering system provide a path for variations at the wheel/ tire assembly to travel to the steering wheel and ultimately to the driver. The steering wheel is the driver interface to the subject system and the tire is the interface with the road surface.

Later in this thesis, a detailed account of a particular SUV program's (code name UXXX) experience developing steering system attributes will be given. The account provides insights into the development process of a large scale and complex system. The development of an automobile steering system cannot be entirely separated from the development of the entire automobile. The product development leaders are continually challenged with decisions and weigh the costs and benefits while determined to produce a successful product as a result. The account of the steering system development focuses on the discovery of the error-state called Nibble and discusses the steps taken to resolve the issue in case-study format. Faced with the problem of Nibble, the program leaders and engineers focused on optimizing the components that were seen as the sources of vibration or natural frequency. The fallacy of this thinking is that, in practice, optimizing the parts does not always lead to an optimized whole.

1.6 Objectives

The objective of this research is not to solve Nibble. The objectives lie more in understanding and documenting the interactions within the steering system to increase system level understanding and therefore improve the execution of system level attributes. Good documentation will help the engineer focused at the component level to not lose sight of the system targets. One of the key questions that this work seeks to answer is; how does a component design engineer keep a system view while working at the component level?

Another objective is to provide another data point for a methodology developed by Qi Hommes (formerly Qi Dong – MIT 1998) where in her PhD work she develops a requirements based matrix methodology by linking Axiomatic Design's Design Matrix (DM) to a Design Structure Matrix (DSM) through transformation. This thesis seeks to use her methodology and provide thoughts on its usefulness regarding steering system attribute development and to develop tools for the design and systems engineers to use.

Other objectives include:

- Organizational and Management - Determine where system integration is needed
- Suggest how to integrate key interfaces – System Integrator (SI) position similar to Ford Body Closures. How would the SI be helpful to chassis?

- Document interactions that influence steering attributes (response, efforts, precision) and error state "Nibble".

1.7 Approach and Methodology

The objectives of this thesis were met through a detailed analysis within the subject scope and context in the following areas:

- Architectural decomposition - Form/function
- Axiomatic Design - DM
- DSM (component/ parameter based)

1.7.1 Architectural Decomposition - Form/Function

In order to understand the interactions and relationships within the chosen system, the system was decomposed to appropriate levels. The chosen system is the automobile steering system. The steering system will be called level 1 where level 0 is the automobile as a whole. The system form was further decomposed to level 2 and then level 3 where the system element was considered component level. The term component is considered loosely where the final level of decomposition was determined by relative usefulness to the analysis rather than arriving at an indivisible part. Many of the elements at level 3 in the analysis can be broken down further but the author considered subsequent levels of decomposition unnecessary to the analysis. As an example, the tire is considered a "component". The tire can be divided into many individual components including; the tread, belts (made up of individual strands of wires and layers of rubber), inner liner (made up of strands of polyester and sheets of rubber), wire bead bundles, sidewalls, wedges, etc.

Functional decomposition is similar to form decomposition but analyzes the functions at each architectural level. For example, the function of the automobile is to provide personal mobility; the function of the steering system is to provide a user interface and directional control. The function of the tire is to provide rolling friction between the road surface and the suspension.

A further discussion on form and function system decomposition is given in section 2.1 and a detailed analysis is given in Chapter 6.0.

1.7.2 Axiomatic Design – DM

Axiomatic Design methods such as the Design Matrix were used to describe the subject system in terms of *what* is to be achieved to *how* it is to be achieved. The 'what' is the function of the system, the 'how' is the form of the system. The functions of the system are referred to as Functional Requirements (FR's) and the form of the system are referred to as Design Parameters (DP's). A square matrix that maps the systems FRs to its DPs is called the Design Matrix. The Design Matrix depicts the relationship between Functional Requirements and Design Parameters.

Axiomatic Design theories are discussed further is Chapter 4.0 and its application to the subject system is presented in Chapter 6.0.

1.7.3 DSM (Requirement/ Component/ Parameter Based)

A methodology of transforming Suh's Axiomatic Design Matrix (DM) to a Design Structure Matrix (DSM) developed by Qi Hommes (Dong 1998) was used to analyze the subject system. The DSM is a square matrix that shows how components or parameters interact within the system. Component and parameter based Design Structure Matrices were used to analyze the subject system. The DSM illustrates multi-component and multi-parameter relationships. DSM theories are discussed further is Chapter 4.0 and its application to the subject system is presented in Chapter 6.0.

1.8 Structure of Thesis

Chapter 2 explains the error state of Nibble in technical terms and discusses the physical system involved as well as a mathematical description.

Chapter 3 is a detailed case study of the events that occurred in the development of the steering system and attributes leading up to and through the launch of the UXXX program. Steering system engineering, tire/ wheel engineering and vehicle dynamics give perspectives of the development events.

Chapter 4 presents several areas of literature findings by the author and discusses briefly some of the author's opinions of what was reviewed. The following topics were researched and reviewed in this chapter:

- Development of requirements – QFD
- Axiomatic Design – the development of design parameters based on functional requirements and the formation of the Design Matrix.
- Design Structure Matrix Methods

- Requirements based DSMs – Transformation of Axiomatic Design's Design Matrix to a DSM.
- Managing interfaces

Chapter 5 presents the methods and tools used in the research to accomplish the objectives and goals. Methods used to analyze the subject system were;

- System (architectural) decomposition
- Functional analysis (decomposition)
- Development of system problem statement
- Interviews
- Axiomatic Design's Design Matrix
- DSM Matrices
- Matrix Addition

Chapter 6 presents the results and analysis provided from the methods and tools used in the research. This section contains analysis of the physical system, a brief analysis of the organization, a discussion of identifying design parameters and functional requirements needed to build the DM and a discussion of comparing the resulting matrices.

Chapter 7 discusses questions arising from the case study and the methods used in the research as well as other discussion topics.

Chapters 8 and 9 finish the work by presenting possible areas of research for future work as well as conclusions and some possible recommendations. Future work, in some cases, are areas beyond the scope of this thesis that the author would have liked to investigate if resources permitted.

2.0 EXPLANATION OF NIBBLE

As mentioned, Nibble is a steering system error-state detected by the vehicle driver at the steering wheel. The driver detects Nibble as a rotational vibration at the steering wheel. This rotational vibration varies from nearly undetectable to severe. Nibble is a function of the magnitude of wheel-end force variation and the level of vehicle sensitivity to the variation. The figure below shows a typical automobile steering system and the important parameters that impact Nibble.

2.1 System Decomposition

A detailed decomposition of the steering system architecture will be given in section 5.0.

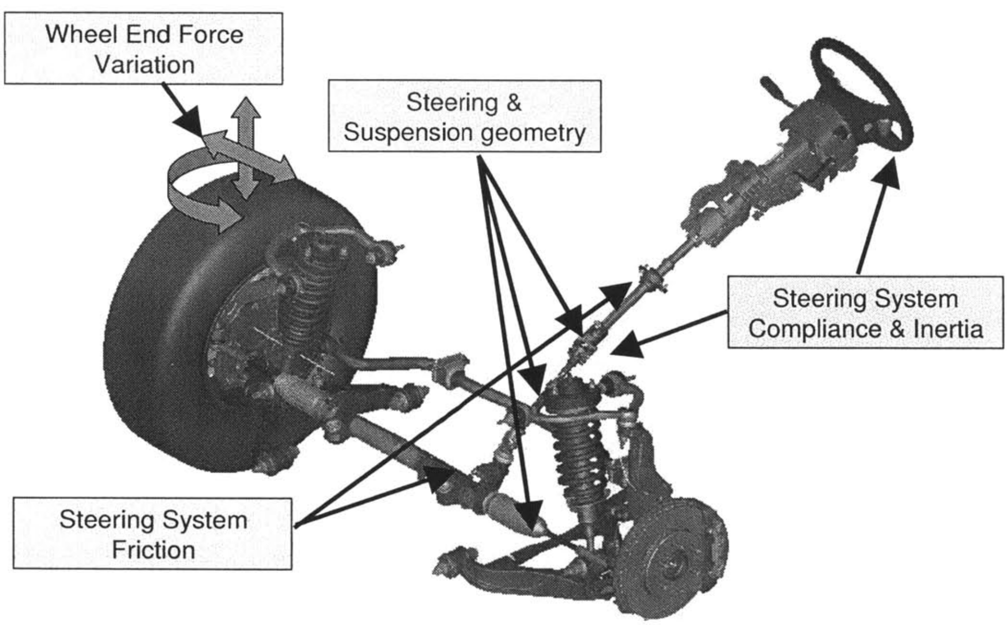


Figure 7: Parameters Affecting Nibble

In many cases, the parameters that cause Nibble also affect other steering attributes such as efforts, precision and response. The following subsystem elements of the steering system will be discussed in more detail with respect to affects on Nibble

- Tires and Wheels
- Hub and Knuckle
- Suspension
- Steering Gear
- Steering Shaft and column
- Steering Wheel

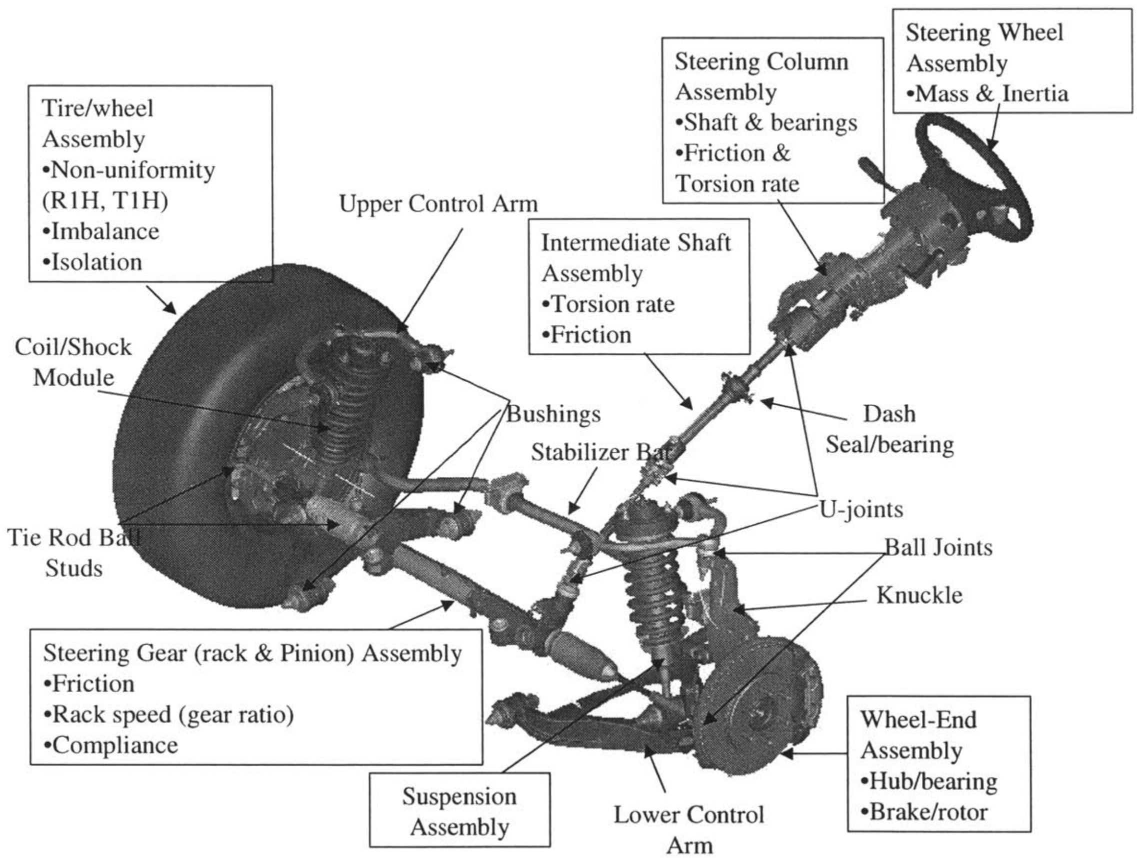


Figure 8: Steering System - Subsystems and Components

2.1.1 Tires and Wheels

In order to describe Nibble fully, we must start where the rubber meets the road – the tire. The first source of controllable system variation is the tire (road surface is an uncontrollable source of variation). Force or run-out variation in the tire will be referred to as tire non-uniformity.

Tire non-uniformity is the variation in the rolling forces of the tire and is measured along the following axes:

- Fz = Radial Force
- Fy = Lateral Force
- Fx = Tangential Force

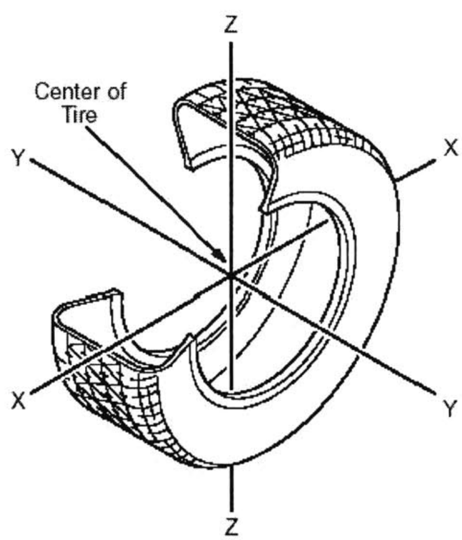


Figure 9: Tire Non-uniformity Forces

Tires can be thought of as a round, rolling spring where the tire sidewalls with air pressure provide a spring rate. Variations in tire construction result in non-uniformity in terms of dimensional run-out and force measurements characterized as Radial and Tangential Harmonics. As the tire/ wheel assembly is rotated through one revolution, the force variation is measured and reveals the waveform shown in Figure 10. The highest peak is referred to as first order or Radial First Harmonic (R1H).

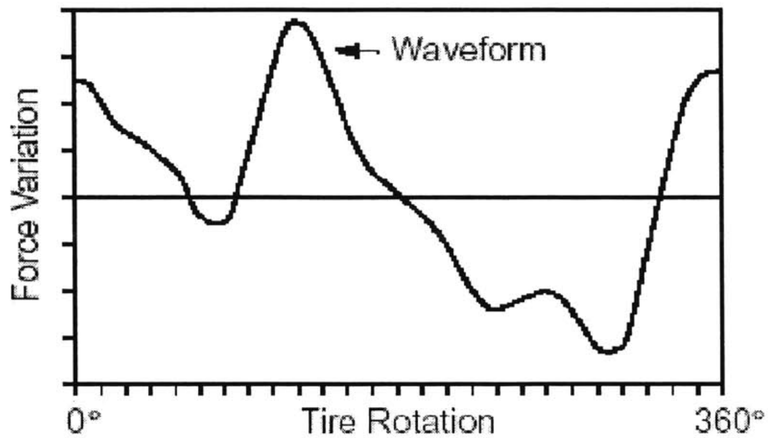


Figure 10: Tire/ Wheel Non-uniformity Waveform

Radial force (Fz) variations are the vertical forces between the tire and wheel that act at the wheel axis.

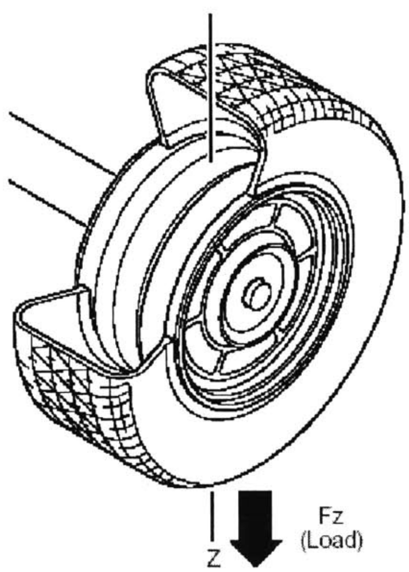


Figure 11: Tire Radial Force (Fz)

Tangential force (Fx) variations act in the fore/aft direction and result in a moment about the suspension ball joints. The cyclical speeding up and slowing down of the tire due to the tangential force variations cause this moment.

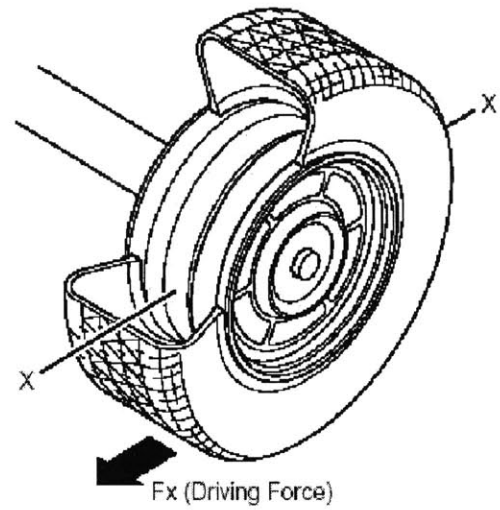


Figure 12: Tire Tangential Force (Fx)

Tire and wheel mass is an important parameter of the steering system where imbalance about the axis of rotation is another source of variation at the wheel-end. The size and mass at the wheel-end also affects the natural frequency of the overall system.

Another source of variation is wheel radial run-out. Radial force variation of the tire and wheel assembly can be reduced by matching the high point of the tire to the low point of the wheel. This matching process is called 'match mounting.' Match mounting offsets the tire and wheel force vectors to create a more uniform tire/wheel assembly.

2.1.2 Hub and Knuckle

Another source of wheel-end run out or variation is the hub pilot to wheel pilot bore fit. Wheels and tires must be serviced at periodic intervals and therefore the wheel must be able to be removed. A minimum gap must be designed between the hub pilot and the wheel pilot bore to allow serviceability. However, if the gap is too large the wheel may not be centered on the hub when the lug nuts are tightened. In the case of UXXX, the lug nuts have a cone shaped interface to the wheel. With natural variation of the stud diameter, wheel cone-seat diameter and location of the wheel pilot bore diameter with respect to true center, perfect concentricity between hub and wheel is rarely achieved. When the cone shaped lug nuts are tightened, the wheel will be pulled to the point where the pilot bore contacts the hub pilot. This lack of concentricity or offset of the wheel to the hub adds to the radial force variation and imbalance that normally exists in the wheel-end subsystem. So, there is a tradeoff between designing the clearance between wheel pilot bore and the hub pilot large enough for serviceability or small enough for vibration.

The knuckle provides structure that connects the hub assembly to the suspension components. The knuckle ball joints are a source of friction and provide the geometry for the steering mechanical advantage. The location of the steering gear tie rods is dependant on the geometry of the knuckle.

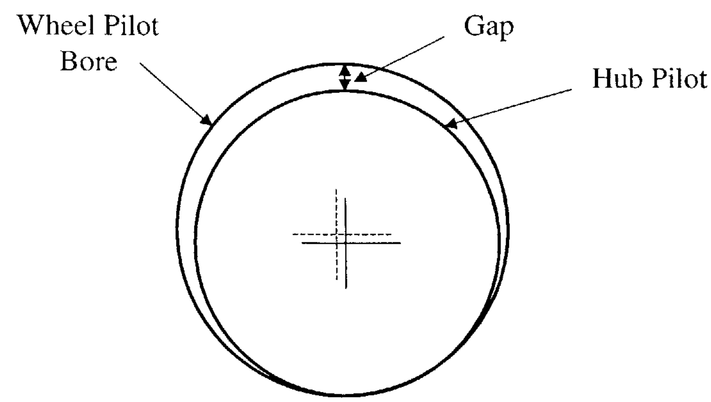


Figure 13: Wheel Pilot Bore to Hub Pilot Gap

2.1.3 Suspension

The suspension system carries the load of the vehicle and provides articulation as the vehicle encounters uneven road surfaces. There are many suspension system designs used in the automotive industry. The suspension design within the scope of this research is a double control arm, coil-over-shock module design. The upper and lower control arms are the connecting points for the steering knuckle. Ball joints are the means of connecting the control arms to the knuckle and allowing pivoting or steering motion. Friction at these ball joints is a factor in Nibble as well as steering efforts. Bushings at the interface between the control arms and the frame provide damping or compliance characteristics that are also a factor in how sensitive a vehicle may be to inputs from the road.

2.1.4 Steering Gear

The steering system within the scope of this research is a rack-and-pinion design as opposed to a re-circulating ball design. The steering gear is the assembly that includes the rack, tie rods, pinion gear and a housing. The key steering gear parameters that affect Nibble and other attributes are gear ratio, ball joint friction and rack friction.

2.1.5 Steering Shaft and Column

The steering shaft includes an upper and lower I-shaft and the column shaft. The column shaft rotates on bearings within the tilt housing. Each section of the shaft is connected by u-joints to allow the shaft to "bend" around various packaging constraints. Bearings and u-joints are a source of friction and therefore affect steering attributes. The sections of the shaft have some give or torsional compliance which also affects steering attributes.

2.1.6 Steering Wheel

The driver interface is the steering wheel. Important parameters considered of the steering wheel are mass and moment of inertia.

2.2 Steering System and Nibble

Nibble can not be blamed on any one component or subassembly within the steering system. In order to be robust to Nibble, the steering system must be insensitive to the normal disturbances at the wheel-end caused by a reasonable level of tire/wheel non-uniformity and imbalance. When Nibble occurs in a steering system that has reasonable non-uniformity and imbalance at the wheel-ends, the steering system is considered sensitive. A sensitive steering system allows small disturbances such as Tangential Radial Harmonic forces at the wheel-end to travel through the nuckle, tie-rods, steering rack, pinion gear and shaft to the steering wheel.

2.3 Nibble Measured in Terms of Frequency

Tire/ wheel non-uniformity contributes to steering Nibble. Nibble is measured by accelerometers position on the steering wheel and generates the frequency plot shown below. As the vehicle's speed is increased, the tire/wheel non-uniformity waveform (R1H and T1H coupled with imbalance) becomes an input to the steering system. When front tire/wheel non-uniformity is at a high enough magnitude and out of phase with each other (right to left), the result is an oscillating force that acts on the steering gear. When these forces exceed the friction in the steering gear, linear displacement is converted to angular displacement of the pinion gear, steering shaft and steering wheel. Angular displacement at the steering wheel is measured as a frequency (Hz). The peak or resonant frequency varies from vehicle to vehicle and may be problematic at highway speeds. The graph below (Figure 14) is a model of the Nibble response where the frequency peaks at just above 15 Hz.

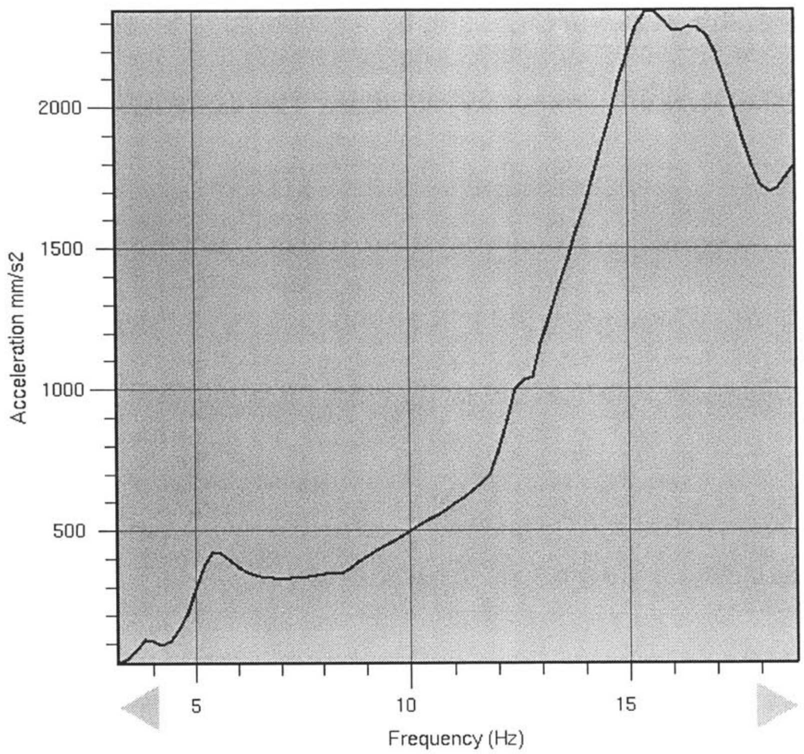


Figure 14: Nibble Response in Frequency (Hz)

2.4 The Mathematics of Nibble

The precise distribution of Nibble can only be determined by Monte-Carlo simulation. However, it is usually estimated to be a simple Weibull distribution. For example, indicating the level of Nibble by "n", the probability distribution for a mean value μ is P(n):

$$P(n) = 1.56 \cdot \frac{n}{\mu^2} \cdot e^{-0.78 \cdot \frac{n^2}{\mu^2}}$$

It is a characteristic of this distribution that the standard deviation, s, is approximately one-half of the mean value:

$$\sigma = 0.52 \cdot \mu$$

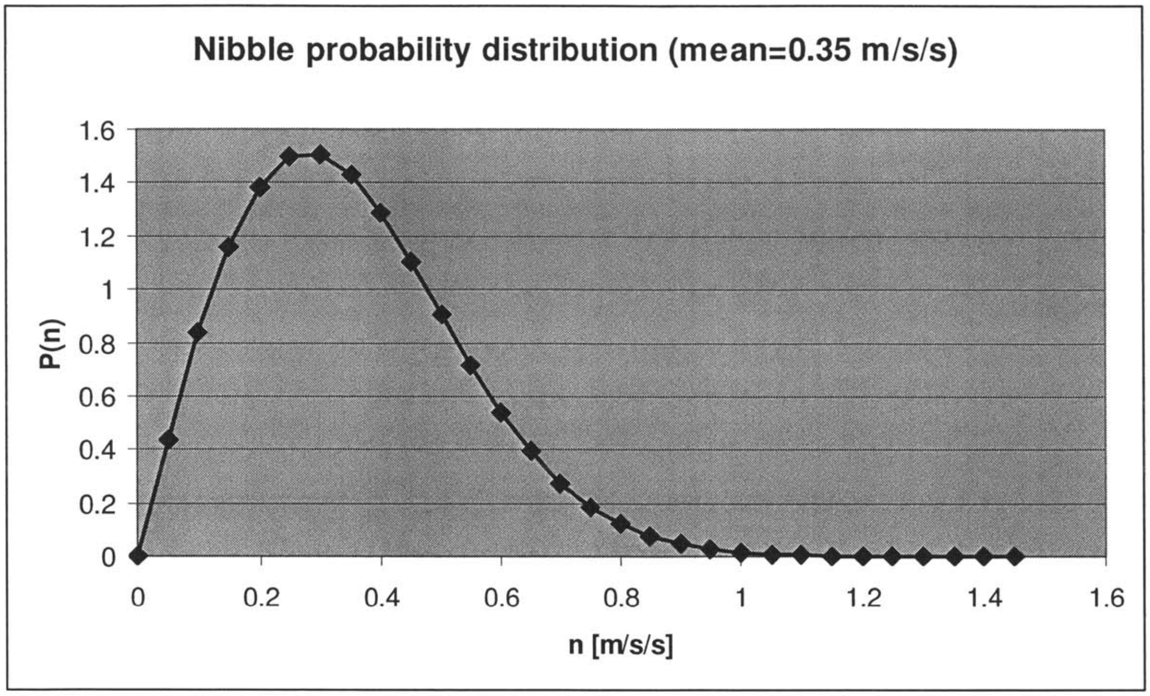


Figure 15: Nibble Probability Distribution

The statistical modeling approach is to factor Nibble into tire-wheel force and vehicle sensitivity and to compute (and later measure) them separately:

Vibration = Force * Sensitivity

Both the sensitivity and the force have considerable variability. The simplification that is made is that, the force is distributed according to a Weibull distribution:

$$P(F) = 1.56 \cdot \frac{F}{\overline{F}^2} \cdot e^{-0.78 \cdot \frac{F^2}{\overline{F}^2}}$$

where we use the "bar" to indicate average.

A normal distribution is expected of sensitivity, S:

$$P(S) = \frac{1}{\sigma(S)\sqrt{2\pi}} \cdot e^{-\frac{(S-\bar{S})^2}{2\sigma^2(S)}}$$

Assuming that S and F are independent, then the mean value of the product is the product of the means:

$$\mu = \bar{n} = \overline{(S \bullet F)} = \bar{S} \bullet \bar{F}$$

while the standard deviation is:

$$\sigma(n) = \sqrt{(\bar{S} \bullet \sigma(S))^2 + (\bar{F} \bullet \sigma(F))^2 + (\sigma(F) \bullet \sigma(S))^2\,)}$$

Now, if the standard deviations are considerably less than the means, and if the fractional variation of the sensitivity is small compared to the sensitivity of the force, then:

$$\sigma(n) \approx \bar{S} \bullet \sigma(F)$$

In this case the resulting distribution is Weibull. Intuitively, if the variation of the sensitivity is small, then the variation in Nibble will be mostly due to force variation [Bagley, et al. (2003)].

3.0 CASE STUDY IN CHASSIS ENGINEERING

The following case study presents facts and events based on first hand experience as well as interviews of involved engineers and managers. The case presents an example of how a large scale program at Ford Motor Company developed key steering attributes and covers events ranging from the beginning of the product development process all the way through to product launch and beyond. Many events are presented in reverse chronological order.

In the weeks leading to Job #1 of the much anticipated all new 2003 sport utility vehicle (code named UXXX), the product development team found themselves scrambling. Long hours and sleepless nights were devoted to resolving the last of the pre-launch issues and concerns and launch this new "best-in-class" SUV.

3.1 The Situation at Launch

After job #1, which came and went in April of 2002, the newly assembled vehicles were parked to await the "OK-to-Ship" authorization. During this pre-determined hold period the units were being inspected and issues were constantly monitored for complete resolution to ensure a perfect launch. After a few weeks of this process the UXXX would receive the "OK-to-Ship" from executives. The UXXX was receiving all the attention of the top executives due to its large scale and potential profitability. It was being called the most important launch in the company since the launch of a completely redesigned mid-size SUV. During the hold period, over 20,000 vehicles were built and parked. Some 15,000 units were stored in a large temporary parking area near the local airport.

One of the issues receiving a great deal of attention during the weeks leading to job #1 and during the hold period before "OK-to-Ship" was an undesirable vibration characteristic called "Nibble". The Nibble concern was affecting management's decision to authorize "OK-to-Ship". During the launch period, a significant percentage of vehicles experienced Nibble and this was one of the primary concerns preventing the "OK-to-Ship" decision. The following sections will explain how the program arrived at launch with such a significant concern from three perspectives; steering system engineering, tire/wheel engineering and the vehicle dynamics engineering.

3.2 Steering System Perspective

During the development stages of the steering system, the steering design and release engineer and suppliers were given the directive to develop a steering system for the UXXX that was very precise. The direction given from upper management was to get as much friction out of the system as possible, reduce compliance as much as possible and deliver as much steering precision as possible. Product development executives selected high performance cars such as the BMW 3 series and X5 as benchmarks for steering attributes.

As engineering sign-off neared, product development executives performed drive evaluations regularly. Development engineers prepared vehicles for these executive evaluations by selecting near perfect tires and wheels. These executive drive evaluations resulted in at least four steering system design iterations, which included more actions to reduce friction and compliance for improved precision. Eventually, a final design was reached and engineering sign-off was authorized. During later pre-production builds, the Nibble concern became more apparent and some of the actions incorporated to reduce friction and compliance were reversed. Ford engineers and suppliers expressed concerns to management that the steering system architecture as designed would not provide robustness to typical variations and inputs from the tires and wheels. After all, no tire is exactly round or perfectly uniform in terms of force variation (see section 2.1.1 on tire non-uniformity) and wheels cannot feasibly be installed to the hub without inducing a small amount of run-out. Even the implementation of industry leading tight tolerances in wheels and tires did not provide a robust capability to overcome the sensitivity of the steering system (and the vehicle) at production volumes.

Upper management insisted that the steering system provide performance-car like attributes and make appropriate trade-offs. Engineers were told that they must work smarter and "think outside the box" to develop a steering system that was both precise *and* robust to Nibble.

3.3 Tire and Wheel Engineering Perspective

During the last prototype builds, which are intended to be saleable units, the tire and wheel group received intense focus concerning Nibble. The tire and wheel design and release engineer, supervisor and manager were all required to attend nightly meetings from 6PM to 8PM to resolve the concern. As vehicles were built, driven, and evaluated, many were found to have the Nibble concern. The tire/ wheel design engineer was tasked with removing and analyzing the tires and wheels of the subject vehicles to determine the root cause of the Nibble, inferring that it was likely the result of something wrong with the tire or wheel, or both. Critical wheel and tire dimensions were measured including pilot bore diameter, wheel radial run-out, and tire/wheel assembly balance and non-uniformity. Many quick fixes were implemented, adding significant unforeseen costs to the program. The changes in tires and wheels were as follows:

- Wheel pilot bore – five iterations of pilot bore diameter configurations and tolerances were implemented. After each change, the supplier was instructed to store previous versions of each wheel for future potential use with the thinking that perhaps later the problem would be resolved and the wheels could be used. Over 33,000 wheels were set aside to await a future decision. The following wheel changes were made leading up to launch:
    1. Changed pilot bore configuration to off-center (off-center bore wheels are wheels where the pilot bore is machined slightly off-center by design to offset tire non-uniformity).
    2. Reduced pilot bore nominal diameter by 0.1 mm
    3. Reduced pilot bore diameter tolerance
    4. Changed pilot bore configuration from off-center back to on-center
    5. Reduced pilot bore diameter tolerance again

- Tire force variation and imbalance specifications were tightened to best-in-class (BIC).

- Wheel/ tire assembly balance – balance specifications in the assembly plant were reduced to equal specifications placed on smaller car assemblies weighing much less. The UXXX tire and wheel assembly weighs about 50% more than typical car wheel & tire assemblies.
- Restricted usage of "ground" tires - tire manufactures typically grind the tread at the shoulder on a percentage of their production to meet OEM force variation requirements. During this restriction period, one major supplier stored over 20,000 tires that had been lightly ground.

3.3.1 Vehicle Repairs

Vehicle repairs were usually accomplished by replacing the wheels and tires with a set of near perfect wheels and tires that were found through sorting.

3.3.2 Key Points – Tire/ wheel system

The Nibble concern and vehicle sensitivity drove requirements of wheels and tires to industry extremes. A survey of wheel and tire suppliers provides understanding that Ford has:

- The tightest wheel pilot bore tolerance among competitors (half the average competitor's tolerance)
- The lowest Radial First Harmonic (R1H) force variation specification for tires among competitors (over 30% less than typical competitor)
- The lowest imbalance requirements

3.4 Vehicle Dynamics Engineering Perspective

The Executive Director of Product Development provided the targets for steering attributes. The European transplant was the one to please. He placed himself in the position of "customer" to the development team and would drive each prototype as they became available. The director stated that he was the customer and that he knew what the American consumer wanted in steering attributes better than they knew. As the development engineers would get a prototype tuned and ready for evaluation, an executive drive would be arranged for the director. Upon completion of the drive event, the director would tell the development team what he liked and what he didn't like. It came to a point where schedule wouldn't permit him to drive all prototypes. At this point quantitative, measurable target ranges were set for each of sixteen specific steering attributes. These target ranges were designed to allow the development team to work toward the end result the executive director wanted without having to involve him every time a new prototype was ready for evaluation. The sixteen target ranges, as set by the executive director, became known as the brand's steering DNA. When the development team achieved the DNA there was a final management drive evaluation for sign-off. Vehicle dynamics engineers work closely with tire/wheel and steering design & release engineers to develop and tune the final vehicle. There are several parameters that can be designed and/or tuned to mitigate a vehicle's Nibble response, as seen in Figure 8.

Steering and suspension geometry had already been decided upon early on the program and any modifications were now out of the question. While the tire engineers focused their efforts on reducing the wheel end force variation through tight tolerances and balancing, it was the task of the vehicle dynamics engineers to balance the steering precision requirements with Nibble robustness through steering system friction, steering compliance, steering wheel inertia, and lower control arm bushings. This was a difficult task, as changes required to impart good steering feel with high precision are generally in direct opposition to what is needed to make a vehicle insensitive to Nibble. However, it was management's directive that the program was to accomplish both good steering precision and no Nibble.

3.5 The Development Process

During the early stages of the UXXX program (prior to prototypes becoming available) limited CAE modeling was utilized to understand Nibble sensitivity. More intensive CAE modeling was done to ensure other steering attributes (response, precision, efforts, etc.) would meet the engineering targets. It was only after the UXXX program received its first prototypes that Ford published the "Tire-Wheel Shake & Nibble Development Guide" which indicated that significant amounts of CAE testing are necessary early in a program to understand production tolerances, tire radial 1^{st} and 2^{nd} order harmonics, tire-wheel assembly imbalance, and wheel pilot-bore and hub pilot clearances, among others. Further analysis outlined in the development guide also states that the information obtained from the CAE models needs to be combined through Monte-Carlo simulations to produce the expected distributions of Nibble for a given program.

Once prototype vehicles were available, physical testing performed by the tire supplier in conjunction with Ford indicated that the 1^{st} order harmonic and wheel balance were the primary parameters that contributed to Nibble. Nibble sensitivity was closely correlated to wheel imbalance through physical tests as shown in Figure 16. Management continued pushing for increased steering precision and feedback feel by insisting on the use of stiffer torsion-bars, since it seemed that Nibble could be fixed with good balancing.

CAE testing, at this point in the program, linked Nibble to vertical responses of the suspension (see Figure 17). However, later in the program it was found that fore-aft modes (tangential forces) were actually more critical than vertical modes. This was an early failure of CAE due to immature modeling capability, especially in regards to friction and damping. VSA (Variation Simulation Analysis) studies were also carried out in CAE, but these analyses only looked at the effects from the vertical suspension modes, thus missing compounding factors. Physical prototype testing on a chassis roll dynamometer also provided misleading results early on.

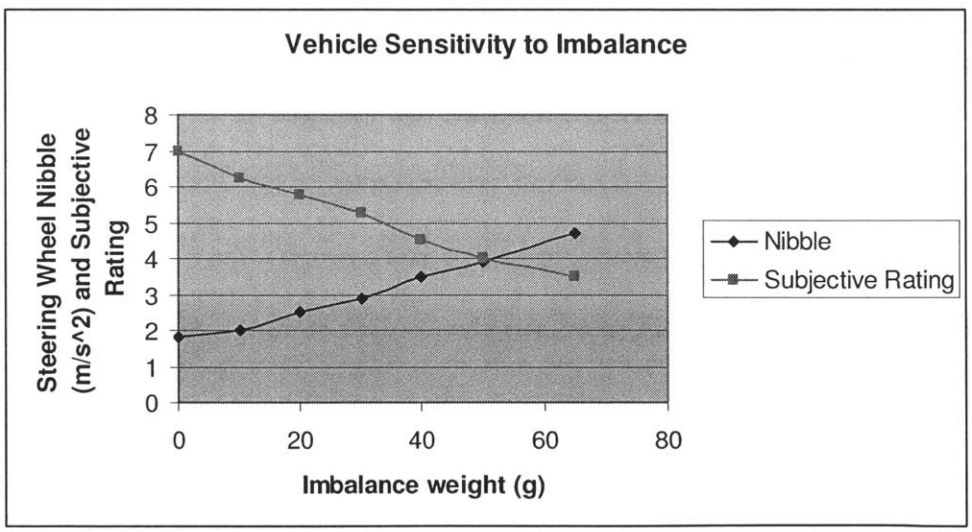


Figure 16: Nibble correlation to Imbalance

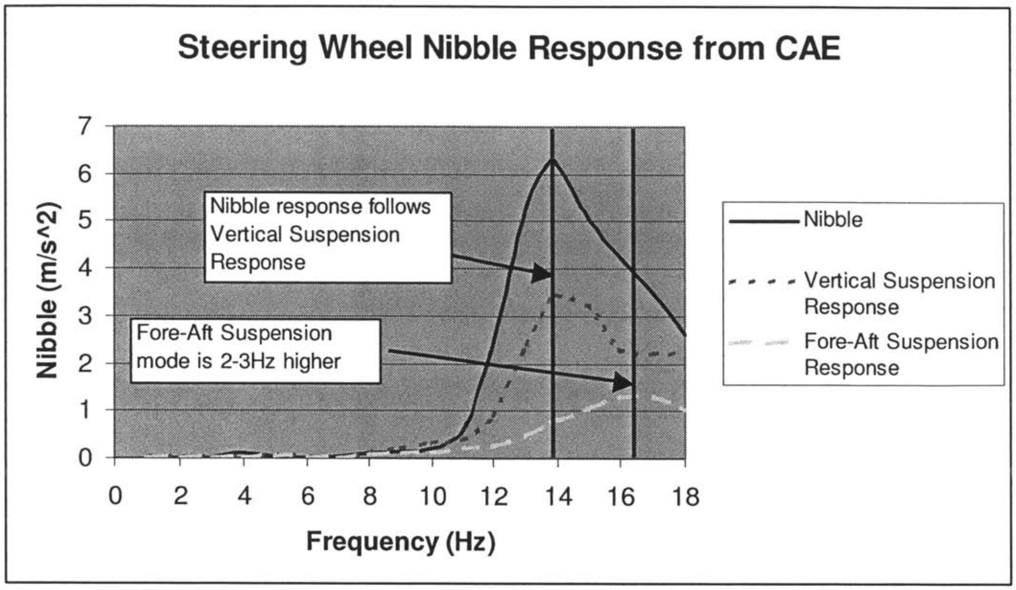


Figure 17: Steering Wheel Nibble Response from CAE

It was only during the last prototype build before Job 1 that management understood the magnitude of the Nibble problem, as a large number of the vehicles produced were exhibiting unacceptable levels of Nibble. A "steering wheel vibration" team (Nibble task force) was put together to quickly resolve this issue prior to going to full-scale production. The team was comprised of executives, managers, and engineers from chassis, noise, vibration & harshness, and vehicle dynamics. The team identified some countermeasures that would degrade some of the steering feel, but seemed promising to mitigate Nibble. However, with proposed countermeasures including increased steering wheel inertia, reduced torsion-bar stiffness, and increased steering system friction, the prototypes showed improvement but still did not meet the Nibble targets (see Figure 18) [Bagley, et al. (2003)].

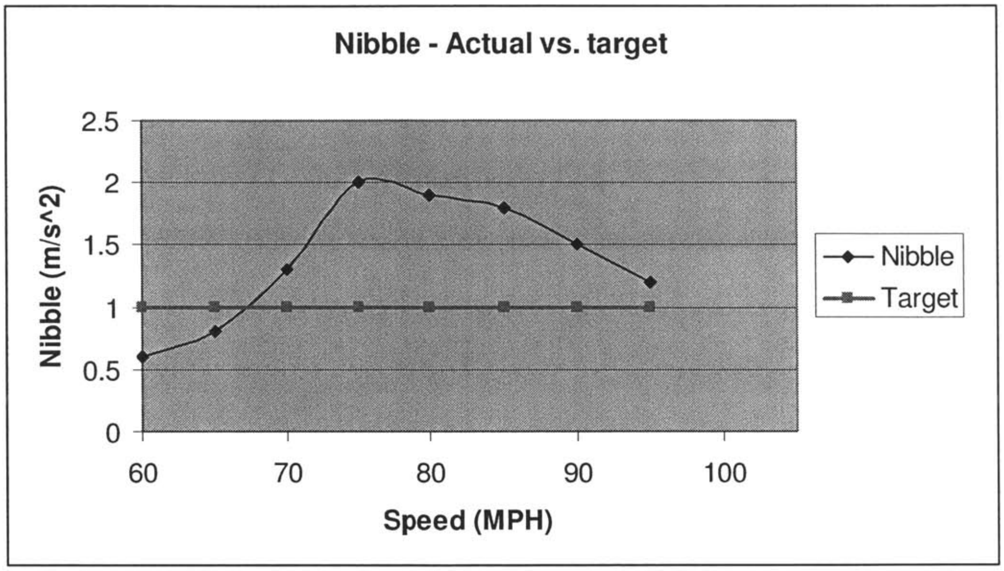


Figure 18: Nibble – Actual vs. Target

Due to the Nibble sensitivity issue still being present with the countermeasures listed above, the tire/wheel suppliers were requested to match-mount the wheels and tires prior to shipping them to the assembly plant. The match mounting process ensures that the inherent imbalance on the tire is placed directly opposite to the imbalance in the wheel, thus creating a counteracting effect. The implementation of the match mounting process, although costly, did provide significant benefit to Nibble subjective ratings in the form of a mean shift and reduced variability (see Figure 19).

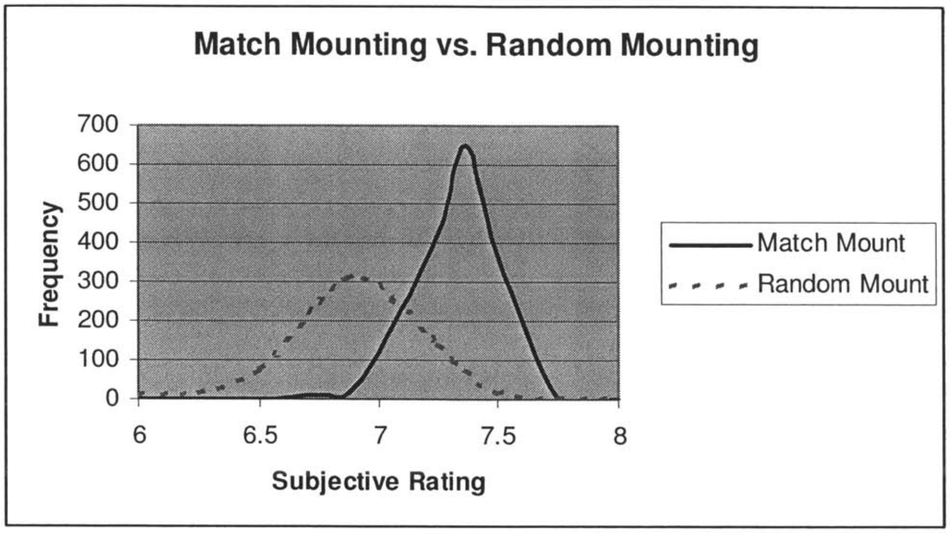


Figure 19: Match Mounting vs. Random Mounting

The sequence of events leading up to Job 1 for the UXXX program is outlined in Table 1. The main factors that led to the Nibble issue late in the program are summarized below:

- CAE modeling not used early enough in the program.
- CAE modeling limitations not well understood and models not validated properly.
- Early physical modeling provided misleading results (possibly due to use of prototypes that were not fully representative).
- Trade-off process between steering precision and Nibble did not follow customer requirements.

When	What
Jan-99	First level prototypes received
Dec-99	Second level protoypes received
Nov-00	Third level prototypes received
	Development Guide published
Jan-01	Nibble testing proposal put forth by Ford & Tire Supplier
Jul-01	CAE predicts nibble follows vertical suspension modes
Oct-01	Protoype testing points to R1H and Wheel imbalance
Nov-01	Process Controls implemented at Tire supplier for R1H
Nov-01	Match Mounting becomes requirement
Apr-02	Job-1

Table 1: Timeline for events on UXXX program

During early development phases, steering engineers were given direction to reduce friction and compliance and increase steering precision as much as possible. During later stages when Nibble became a significant concern, steering system engineers, tire/ wheel engineers and vehicle dynamics engineers as well as many others were tasked to resolve Nibble by improving wheel and tires and adding back in friction (reducing sensitivity). The engineering activities during the later stages in the UXXX program are shown in Figure 20 below.

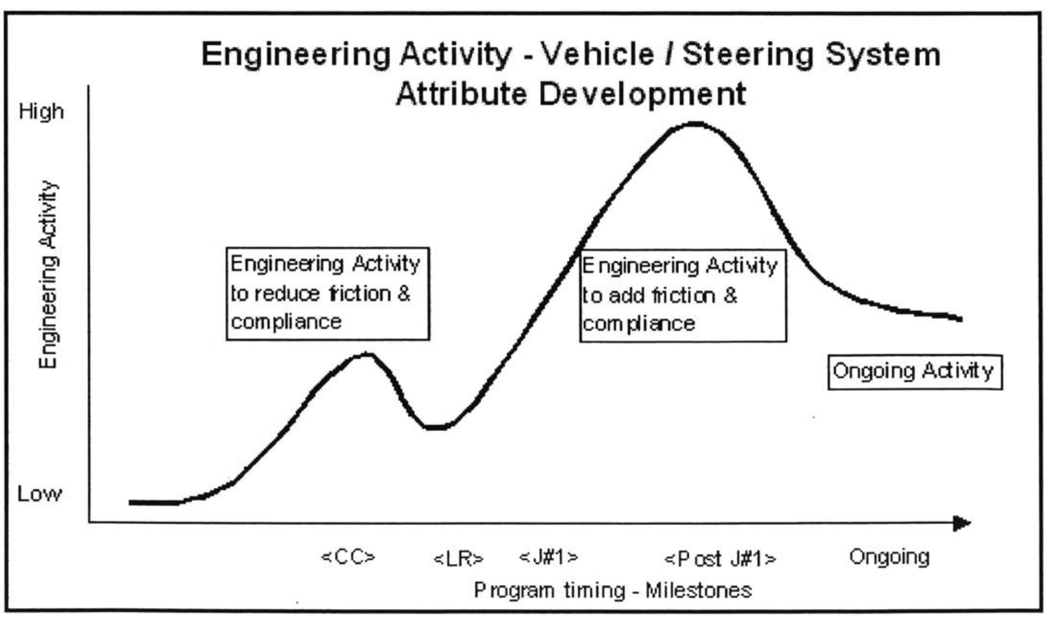


Figure 20: Engineering Activity Timeline

This graph shows how engineering activities and effort varied from the weeks before the <CC> milestone (change cut-off, engineering sign-off), <LR> milestone (launch readiness, 1PP pre-production build) and through job #1 and beyond. The curve is also a representation of program costs with respect to the Nibble concern. See Appendix 2 for a historical perspective on changes made that reduced system sensitivity.

3.6 Consequences

- 33,000 wheels stored to accumulate storage costs. Significant quantity later scrapped at cost of nearly $700K.
- Warranty and Customer satisfaction worse than previous vehicle (Figure 21)
- Ford bought back several vehicles
- "Best-in-Class specifications on wheels and tires roughly equal to $25 per vehicle, or nearly $6 Million per year in incremental variable cost.

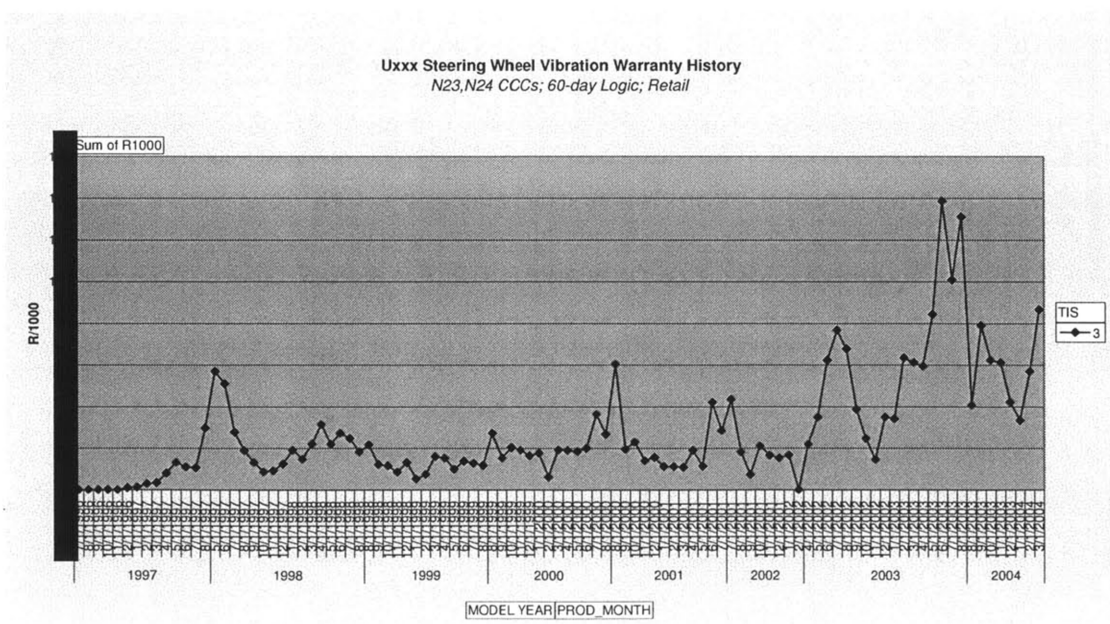


Figure 21: UXXX Steering Wheel Vibration Warranty History

The following graph compares the subject Ford vehicle and its important competitors.

Parameter	Ford UXXX	Competitor	Fords cost vs. Competition
Measure and mark wheels	Yes	No (most)	⇧
Measure and mark tires	Yes	No (most)	⇧
Match mount tires and wheels	Yes	No (most)	⇧
Wheel pilot bore tolerance	+/- 0.025 mm	+/- 0.035 mm	⇧
Tire R1H	12 lbs	15 lbs (Typical)	⇧
Nibble (warranty and customer satisfaction)	High	Low (Figure 22)	⇧

Table 2: Tire/ Wheel Parameters – Ford vs. Competition

Figure 21 (below) clearly reveals the negative impact of system decisions. The vertical axis is TGW/1000. TGW means that a customer reported a "thing gone wrong" with the vehicle. From 1998 through 2002 the UXXX was averaging about 18 TGWs per 1000 vehicles showing a small amount of unsteady improvement. GM however, shows steady improvement to below UXXX performance. In 2003 a new UXXX was introduced with significant architectural differences. The plot shows steering wheel vibration increasing drastically for 2003 and 2004. These data show the impact of management decisions discussed in the case.

As mentioned in the case, program leadership was unyielding in their desire for low friction and compliance while expressing a lack of concern for the potential error-states early on. As the program neared launch, different managers (manufacturing) exerted power and influence over the acceptability of the vehicle.

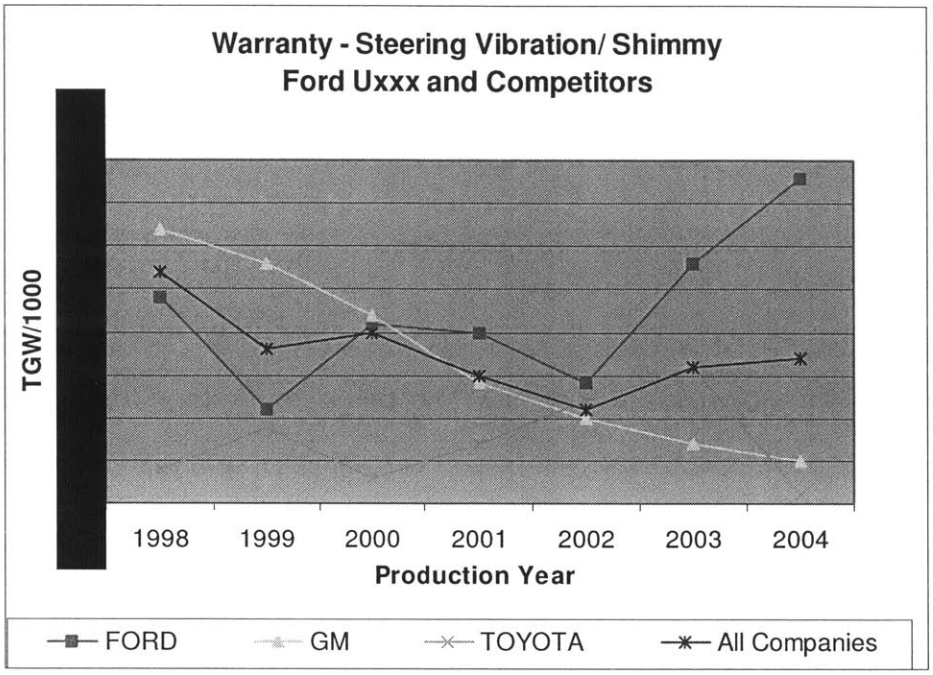


Figure 22: Ford UXXX vs. Competitors – Steering Wheel Vibration

3.7 Questions from Case

The case causes the following questions to be asked:

- How can "Nibble" be prevented?
- Can steering system attributes be executed without error states?
- What organizational aspects allowed this to happen?
- Does the direction to remove as much friction and compliance as possible make sense... Can it be shown in the DSM that it doesn't?
- Can story in case be found in DSMs?

EACH QUESTION ABOVE WILL BE DISCUSSED IN CHAPTER 7.0.

4.0 LITERATURE REVIEW

This thesis is scoped such that the product or system in question is mature in nature. That is to say, the concept of the subject steering system is pre-existing and has existed for many years in its present generic form. However, a mature system does not mean an optimized system. There are many elements that interact and can be varied in a way that can produce an almost infinite set of outputs. Parameters of the system can be altered to achieve ongoing improvements. In order to understand the subject system and systems engineering a literature search was conducted in the following areas of interest:

- Development of attribute requirements in product development
- Axiomatic Design and the Design Matrix (Suh)
- Design Structure Matrix (DSM)
- DM Transformation to DSM (Qi Hommes)
- Requirement flow down
- System Integration

4.1 Development of Attribute Requirements in Product Development

A key assumption made in this research is that customer needs have been appropriately identified. After subjective customer needs are identified, more specific and measurable targets for the system attributes need to be developed. Targets or specifications need to be measurable so that they can be verified upon completion of the design. Ulrich and Eppinger state that "product specifications do not tell the team how to address the customer needs, but they do represent an unambiguous agreement on what the team will attempt to achieve in order to satisfy the customer needs."

One of the most important challenges in product development is the step between identifying customer needs and establishing the product specifications. This step is the *translation* of customer needs to a measurable specification or target. For example, a target customer says they want good response in a vehicle steering system. The product development team must be able to effectively translate this stated need of the customer to meaningful specifications and complete the loop by verifying with the "customer" that execution of the specification does in meet his/ her expectation.

There have been many methods established that effectively manage customer needs through to product specifications. One of the most popular methodologies is Quality Function Deployment (QFD).

QFD originated in Japan and was developed to transfer the disciplines of quality control in manufacturing to the product development process. The Systems Engineering Fundamentals Reference Guide of Ford Motor Company describes QFD as a planning tool used to translate the voice of the customer into appropriate product specifications. QFD takes actual customer statements and, through several phases, incorporates them in the product features with the end goal to be complete customer satisfaction and acceptance. QFD has the following four phases:

- **Phase I - Product planning:** establishes customer requirements, rationalizes, translates into Technical Performance Measures (TPM).

- **Phase II - Design Development:** The best of the product design concepts meeting the TPMs are selected.
- **Phase III - Process planning:** Alternative manufacturing processes are selected and process operations and parameters are identified.
- **Phase IV - Production Planning:** Consideration is made to controlling the process, ensuring that the process parameters are achieved consistently and the resulting product meets the customer requirements.

One of the most well known elements of the QFD process is the tool called the House of Quality (HoQ). The House of Quality is a comprehensive matrix developed by a multidisciplinary team that documents and manages customer requirements, benchmarking data, Technical Performance Measures and decisions. See Figure 23 for an example of the House of Quality matrix (source Hauser and Clausing).

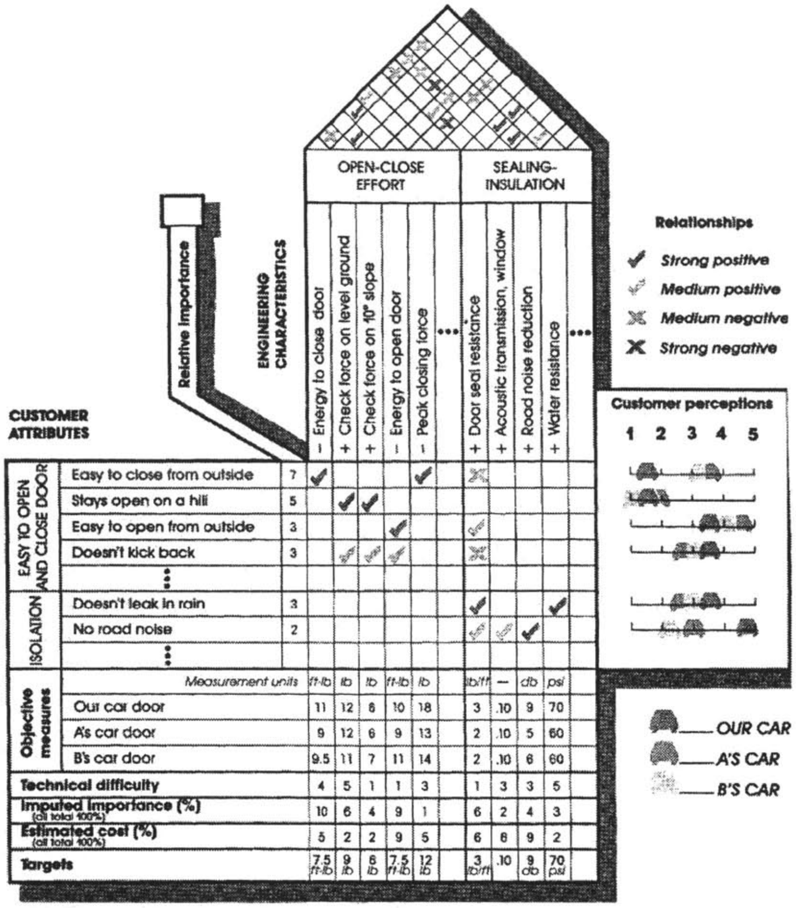


Figure 23: Example of House of Quality – QFD

QFD is said to deliver the following benefits when executed in a disciplined manner:

- Reduced time to market
- Reduction in design changes
- Decreased design and manufacturing costs
- Improved quality
- Increased customer satisfaction

In addition to the House of Quality matrices, QFD utilizes several other management and planning tools including:

1. Affinity diagrams
2. Relations diagrams
3. Hierarchy trees
4. Matrices and tables
5. Process Decision Program Diagrams (PDPC)
6. The Analytic Hierarchy Process (AHP)
7. Blueprinting

Ford Motor Company does not officially use QFD for translating customer statements into design features but has adapted many of the principles. The table below shows some of the similarities between Ford's PALS process and QFD. Both methods seem to be suited for mature products where analysis of customer opinions about features of existing products can help to make improvements and prioritize engineering efforts. QFD or PALS do not seem to be well suited for radically new products where a technology may be new and innovative.

The following table compares and contrasts QFD principles and Ford practices. Through studying QFD and discussions with those experienced in the Ford target setting processes we are able to see similarities as well as differences in approaches to translating customer requirements and cascading them to objective engineering requirements at all levels of the system.

QFD vs. Ford Targets Process

	QFD	Ford Targets Process
Customer attributes	Obtained as voice of customer and presented in HoQ	Input from Marketing, driven by quality data, represented in PALS matrix.
Engineering Characteristics	Defined by relationships and affect on customer attributes, presented in HoQ	Relationship to customer attributes is unclear from my experience. Requirements are standardized set of specifications.
Customer relative importance	Presented in HoQ, compared to customer perception of attributes compared to competitors	Competitive and benchmark data is considered when developing PALS matrix.
Objective measures	Presented in HoQ with relationships to customer attributes.	PALS includes objective measures where possible.
Cascading requirements	A series of HoQ's are developed linking the voice of the customer to downstream activities such as manufacturing.	Target cascade in System Engineering "V" to subsystem levels from vehicle level. Limited clarity of relationships.

Table 3: QFD vs. Ford Targets Process

Ulrich and Eppinger suggest five steps to setting final specifications including:

1. Develop technical models of the product.
2. Develop a cost model of the product.
3. Refine the specifications, making trade-offs where necessary.
4. Flow down the specifications as appropriate.
5. Reflect on the results and the process.

The case previously presented provides an illustration of how challenging it is to develop and execute appropriate product specifications. In the case of steering attribute development, executives desired a low friction and low compliance system and were unwilling the make necessary trade-offs with certain error states. Had technical models been available early enough, costly prototypes and trial and error development could have been avoided.

4.2 Axiomatic Design and the Design Matrix

Axiomatic design is a comprehensive engineering design theory pioneered by Nam Suh. For the purposes of this research, a brief explanation will be given with more focus on the design matrix.

Nam Suh (2001) defines design as an "interplay between *what* we want to achieve and *how* we want to achieve it… where a rigorous design approach must begin with an explicit statement of "*what* we want to achieve" and end with a clear description of "*how* we will achieve it." Once we understand the customer's needs, this understanding must be transformed into a minimum set of specifications that adequately describes, "What we want to achieve" to satisfy the customer's needs. The descriptor of "how to achieve it" may be in the form of design parameters (DPs)."

Suh defines the minimum set of customer requirements as functional requirements (FRs). Functional requirements map to design parameters as shown in Figure 24.

Definition of Design

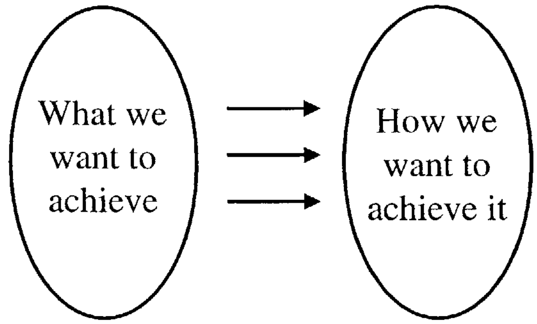


Figure 24: Definition of Design (Suh 2001)

According to Suh, the ultimate goal of axiomatic design is to "establish a scientific basis for design and to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought processes and tools."

Key axiomatic design definitions (Suh 2001):

Functional Requirement: Functional requirements (FRs) are a minimum set of independent requirements that completely characterizes the functional needs of the system in the functional domain. By definition, each FR is independent of every other FR at the time the FRs are established.

Constraint: Constraints (Cs) are bounds on acceptable solutions. There are two kinds of constraints: input constraints ad system constraints. Input constraints are imposed as part of the design specifications. System constraints are constraints imposed by the system in which the design solution must function.

Design Parameter: Design Parameters (DPs) are the key physical variables in the physical domain that characterize the design that satisfies the specified FRs.

Axiomatic design theorizes that all design is represented in four domains:

1. Customer Domain: where customer needs, expectations and requirements are specified.
2. Functional Domain: where the functional requirements that satisfy every item in the customer domain are specified.
3. Design Domain: the actual designed form that satisfy the functional requirements.
4. Process Domain: where the process required to achieve the design parameters is specified.

4.2.1 Building the Design Matrix (DM)

Axiomatic design's design matrix (DM) is the mapping of functional requirements (FRs) to design parameters (DPs) in the form of a square matrix. The design matrix is based on Suh's first axiom of design, the independence axiom. The Independence Axiom states, "When there are two or more FRs, the design solution must be such that each one of the FRs can be satisfied without affecting the other FRs." A matrix form (DM) of the FR to DP relationship can be shown as follows:

FR1		X	0	0		DP
FR2	=	0	X	0		DP
FR3		0	0	X		DP

Figure 25: Matrix form of FR and DP Relationship

The design matrix can be used to analyze how good a particular design is. Axiomatic design's theorem 4 states that "in an ideal design, the number of DPs is equal to the number of FRs and the FRs are always maintained independent from each other." This theorem is represented by the matrix above where all FR to DP relationships fall on the diagonal and is said to be uncoupled.

Matrices that show off-diagonal interactions between FRs and DPs indicate a less than ideal design. A design is said to be decoupled and acceptable when the design matrix can be rearranged such that interactions between FRs and DPs fall below the diagonal. A design is said to be coupled and poor when the design matrix shows interactions above the diagonal.

4.2.2 Transforming DM to Diagonal or Lower Triangular

According to Suh, "any matrix can be mathematically transformed into a diagonal matrix." In the case of the Design Matrix, coupled interactions are either eliminated through good design methods or mathematically moved to either the diagonal or the lower triangle of the matrix. In Chapter 5.0 a DM is constructed and transformation to lower triangular is attempted using an algorithm developed by Eric McGill (LFM 06). Other matrix partitioning algorithms have been written and used with success including one by Qi Dong (1998).

The validity of the statement that "any matrix can be mathematically transformed into a diagonal matrix" is further discussed in Chapter 6.0.

4.3 Design Structure Matrix (DSM)

The history of Design Structure Methods (DSM) dates back to 1973 (Warfield) and 1980 (Steward). Since then many others including Dan Whitney, Steve Eppinger and Qi Hommes of MIT have further developed methods using Design Structure Matrices. Methods have been developed for systems analysis (component and parameter based), project management (task based) and organizational analysis (team based). The following DSM methods will be discussed in this section:

- DSM as a Project Management Tool
- DSM as a System Analysis Tool
- DSM as an Organizational Analysis Tool

The Requirements Based DSM developed by Qi Hommes (Dong 2002) will be discussed in the next section.

4.3.1 DSM as a Project Management Tool

- Activity or task based
- Diagrams information flows in complex projects
- Traces impacts of decisions
- Can be a consensus document for the project team
- Helps team members see the big picture
- Helps the project manager (notification, reviews)
- Helps sequence tasks
- Highlights iterative tasks

4.3.2 DSM as a System Analysis Tool

- Component or Parameter based
- Provides a visual image of important relationships in a product development project
- Captures and displays a process
- Acts as a focus for process analysis and re-engineering
- Reveals key information flows
- Discovers previously unknown patterns: product architecture & organizational architecture
- Shows people where they fit
- Represents types of interactions including:
    - Spatial
    - Energy
    - Information
    - Material

4.3.3 DSM as an Organizational Analysis Tool

- Team based for organizational analysis
- Information flow among organizational entities
- Identifies required communication flows in the following types:
    - Level of detail
    - Frequency
    - Direction
    - Timing
- Manipulate matrix to identify clusters of highly interacting teams and individuals and minimize inter-cluster interactions
- Helps organizational design

A DSM is a matrix representation of the interactions or dependencies within a system, project or organization. MIT's DSM website (www.dsmweb.org) tells us that there are three basic building blocks for describing system element relationships: parallel (concurrent), sequential (dependent) and coupled (interdependent).

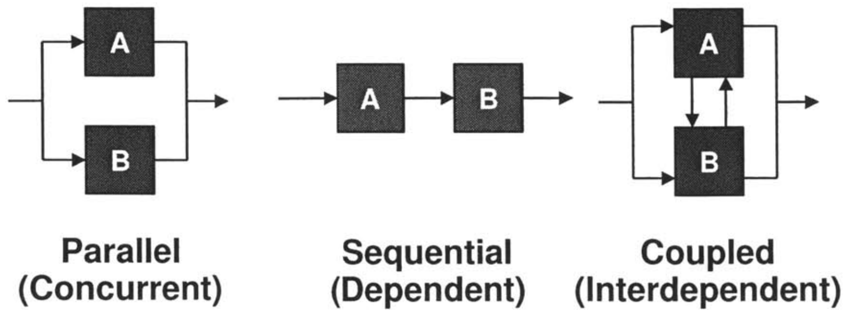


Figure 26: Building Blocks to Describe System Element Relationships

Elements with a parallel relationship do not interact with each other. When two elements are in parallel with each other they are said to require no information from each other or interact in any way.

Elements in a sequential relationship indicate that one element influences the behavior or decision of another. In the case of a project, this means that the one task must be completed before the other task is started.

Elements in coupled relationship are dependent on each other. Element A influences B and B influences A. In a project situation, this relationship means that task A must provide information to task B and B to A. Task A can be done to a point where B provides information. Then task A is revisited. Task A and B are then completed in an iterative manner.

In a parameter or component based system, coupled elements are connected or depend on each other. Two gears are a good example of coupled components. In the case of the steering system, the rack gear cannot function independent of the pinion gear. They are represented as coupled elements in the DSM.

4.4 Requirements Based DSM

One of the main objectives of this work is to provide case study research to add to and evaluate the systems analysis methodology developed by Qi Hommes [Dong, Q., (2002)]. In her work she discovered in literature "that the Design Structure Matrix method can help manage system interactions but is difficult to apply to early phases of the design process, while the Axiomatic Design's Design Matrix can predict system interactions early on."

Hommes determined that there are certain weakness and strengths of Axiomatic Design's Design Matrix and the Design Structure Matrix methods. For more information please refer to Qi Hommes thesis titled: Predicting and Managing System Interactions at Early Phase of the Product Development Process (2002). In her research, she develops a methodology where a systems analysis begins with the development of Axiomatic Design's Design Matrix (DM) using Suh's principles of Axiomatic Design. The Design Matrix is then transformed into a DSM using a matrix transformation method.

Hommes' research claims that by combining the strengths of both the DM and the DSM methods we would have a way to accomplish the following:

- Reduce the amount of system coupling using good system design concepts.
- Forecast system interactions before the detailed design phase.

- When system couplings cannot be avoided due to certain constraints, apply systems analysis tools to manage system interactions, to improve efficiency of system interactions.
- Capture system emergent properties as the design work is carried out. Reflect the emergent properties back to the requirements they affect.

4.4.1 Matrix Transformation Method

Hommes matrix transformation method involves three steps (for further details refer to Qi's 2002 MIT PhD thesis):

Step 1: Construct an Axiomatic Design Matrix

	DP1	DP2	DP3
FR1	X	O	X
FR2	X	X	O
FR3	O	X	X

Step 2: Choose the output variables in each row (circled).

	DP1	DP2	DP3
FR1	X	O	X
FR2	X	X	O
FR3	O	X	X

Step 3: Construct the final DSM by permuting the rows of the DSM to move the output variables to the diagonal position.

	DP1	DP2	DP3
DP1	X	X	O
DP2	O	X	X
DP3	X	O	X

See Chapter 5.0 for application of the DM to DSM transformation methodology for steering system.

Hommes concludes that for engineering design activities the diagonal interactions should be used as input variables when transforming the Design Matrix to a DSM. When this principle is applied, the DSM interactions are equivalent to the DM interactions when the DM Functional Requirements (FRs) are replaced by the Design Parameters (DPs.).

4.5 Interface Management (or System Integration)

This section is somewhat a departure from previous sections in that rather than researching a method or tool for system analysis, it is more a study of how to take the work done at lower system levels and integrate them to deliver system level requirements. It does not question the correctness of the system level requirements. It is assumed that the system level requirements are appropriate and were a good translation of customer requirements.

Interface management or system integration is the overall management of the system with the objective of executing the system level requirements. A complex system cannot be designed and developed by one person. The development of an automobile for example is not a one-person job. Hundreds of individuals work separately, yet together in overall purpose, to design thousands of components. These hundreds of engineers and thousands of components will ultimately deliver one system with specific system level requirements. In order to accomplish a complex task like designing an automobile, the design activity must be divided (partitioned) in a way that reduces complexity. Simply dividing the work into smaller chunks will not necessarily produce good results. Maier and Rechtin suggest that responses to complexity apply throughout system development and "that the concept that complex systems can be progressively partitioned into smaller and simpler units – and hence smaller problems – omits an inherent characteristic of complexity; the interrelationships among the units. As a point of fact, poor aggregation and partitioning during development can *increase* complexity, a phenomenon all too apparent in the organization of work breakdown structures."

So how does an organization manage the hundreds or thousands of interfaces where many functional departments and hundreds of engineers are doing the work and hope to accomplish the goals of the system?

Maier and Rechtin state that the "primacy of complexity in system design helps explain why a single "optimum" seldom if ever exists for such systems. There are just too many variables. There are too many stakeholders and too many conflicting interests. No practical way may exist for obtaining information critical in making a "best" choice among quite different alternatives."

Maier and Rechtin point out important differences in how hardware is developed vs. how software is developed. This is due to the advent of more software-intensive systems, which has led to a paradigm shift in system design. Maier and Rechtin make the following recommendations; "When the cost of software development dominates, development systems should be organized to simplify software development. But good software architectures and good hardware architectures are soften quite different. Good architectures for complex software usually emphasize layered structures that cross many physically distinct hardware entities. These are in contrast to the emphasis on hierarchical decomposition, physical locality of communication, and interface transparency in good hardware architectures."

The subject of this thesis is hardware specific where good architecture requires appropriate partitioning, hierarchical decomposition, good communication and interface transparency.

Good interface management requires a systems approach to development. The system architect for the automobile is the Chief Engineer. At the first subsystem level (e.g., chassis), the functional chief engineer comes as close to the system architect as possible at Ford Motor Company. At the next subsystem level (e.g., steering system) we cannot identify a clear "architect". Based on the literature review and experience at Ford Motor Company, it is clear that and "architect" should be identified at significant levels of the architectural hierarchy.

The literature (Maier & Rechtin) states that the architect's "greatest concerns and leverage should be with the systems' connections and interfaces because (1) they distinguish a system from its components; (2) their addition produces unique system-level functions, a primary interest of the systems architect; (3) subsystem specialists are likely to concentrate most on the core and least on the periphery of their subsystems, viewing the latter as external constraints on their internal design. Their concerns for the system as a whole is understandably less that that of the systems architect – is not managed well, the system functions can be in jeopardy."

From the literature review we can conclude that in practice at Ford Motor Company, the system (automobile) engineer matches the organization where there is a chief engineer responsible for the system as a whole. At the fist subsystem level, such as chassis, there is a chief functional engineer that parallels the responsibilities of an architect at that level. At the second subsystem level, steering system, a responsible "architect" or integrator does not clearly exist. Further discussion and recommendations will be presented in Chapters 7.0 and 9.0

5.0 METHODS

This section presents a detailed analysis of the subject system using the methods presented in section 1.7 (methodology).

5.1 Methods

The following steps summarize the methods followed for analysis:

1. A system was selected for analysis
2. Analysis of system was accomplished through architectural decomposition, both form and function
3. The system was decomposed to a level (level 4 as defined in section 5.2.2) that would aid in developing a better understanding of system interactions and attributes. Decomposition was accomplished through interviews of subsystem and component engineers.
4. Construct and analyze preliminary DSM of physical (spatial) interactions.
5. Primary and secondary functions were determined for each level 4 "component" through interviews.
6. Components are labeled as Design Parameters (DP) and their respective functions are labeled as Functional Requirements (FR).
7. The relationships between Design Parameters and Functional Requirements were determined through interviews. Relationships between DP's and FR's are interactions.

8. Design Parameter and Functional Requirement interactions were mapped against each other in the form of a square matrix called a Design Matrix (Suh's Axiomatic Design)
9. Subsystem functions were obtained through existing subsystem/component P-diagrams.
10. P-diagrams were obtained and functions were separated into primary functional requirements (FR) and constraints (C).
11. Interviews were conducted to determine the form, or design parameters (DP) that deliver the primary functions of each subsystem.
12. The interactions of P-diagram functions (FR) and design parameters (DP) were determined and mapped in a Design Matrix.
13. Design Matrices from steps 7 and 11 were compared and combined to form one list of FRs and DPs
14. Interactions between FRs and DPs were re-evaluated and mapped in a DM with side-effect interactions identified
15. The combined Design Matrix was transformed into a component based Design Structure Matrix using Qi's methodology.
16. Steering attributes were determined by interviewing Vehicle Dynamics engineers.
17. Steering system components were assessed according to their influence on steering system attributes (Nibble, efforts, precision and response) (interviews with Vehicle Dynamics).
18. Relationships between components and Nibble were determined and mapped on DSM.

19. Side-effect, spatial and attribute interactions were combined into one DSM
20. System parameters that influence steering attributes were determined by interviewing Vehicle Dynamics and steering system engineers
21. Matrices were partitioned to analyze coupled parameters and components.

5.2 Research Methods Discussed

The Design Matrix developed in Steps 5 – 8 is referred to as DM2 where Design Parameters were defined first and then Functional Requirements were determined by reflection (see Figure 27). That is, instead of understanding the function first, the form was determined first. Each form or component has a given function. This is what is meant by reflection.

The Design Matrix developed in steps 9 – 12 is referred to as DM1 (Figure 27). DM1 was developed by first understanding the required functions of the subsystem through reference to existing P-diagrams. Important parameters of the component or subsystem were determined by asking experts what part of the subsystem delivered the intended the function.

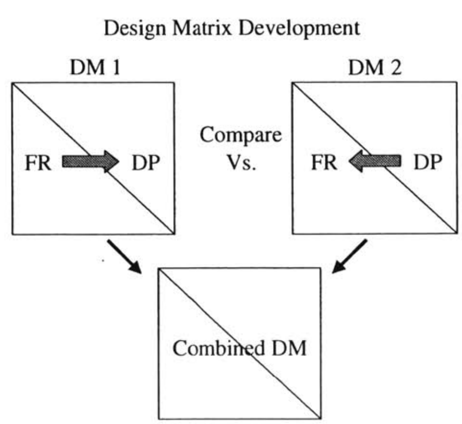


Figure 27: Design Matrix Development Methodology

The combined DM resulted from the increased understanding of the system when analyzing it from each direction. That is, insights were obtained from both methods and lead to improved definition of functional requirements and design parameters. In looking back at how the methodology evolved, it can be compared to the zigzag methodology discussed by Suh where the first step is to define the high level functional requirement of the subject system. Functional requirements and design parameters are separated into domains previously discussed, 'what we want to achieve' and 'how to achieve it'. In this case, what we want to achieve is personal mobility. Within the context of this research, the 'how to achieve' mobility is by means of the automobile. A functional requirement of the automobile is control over direction. Directional control is achieved by the steering system. Directional control is the functional requirement and the form or design parameter is the steering system. This pattern is followed again when considering the requirements of the steering system. Steering system requirements lead to subsystem form. The zigzagging approach eventually leads to the system form at the component level.

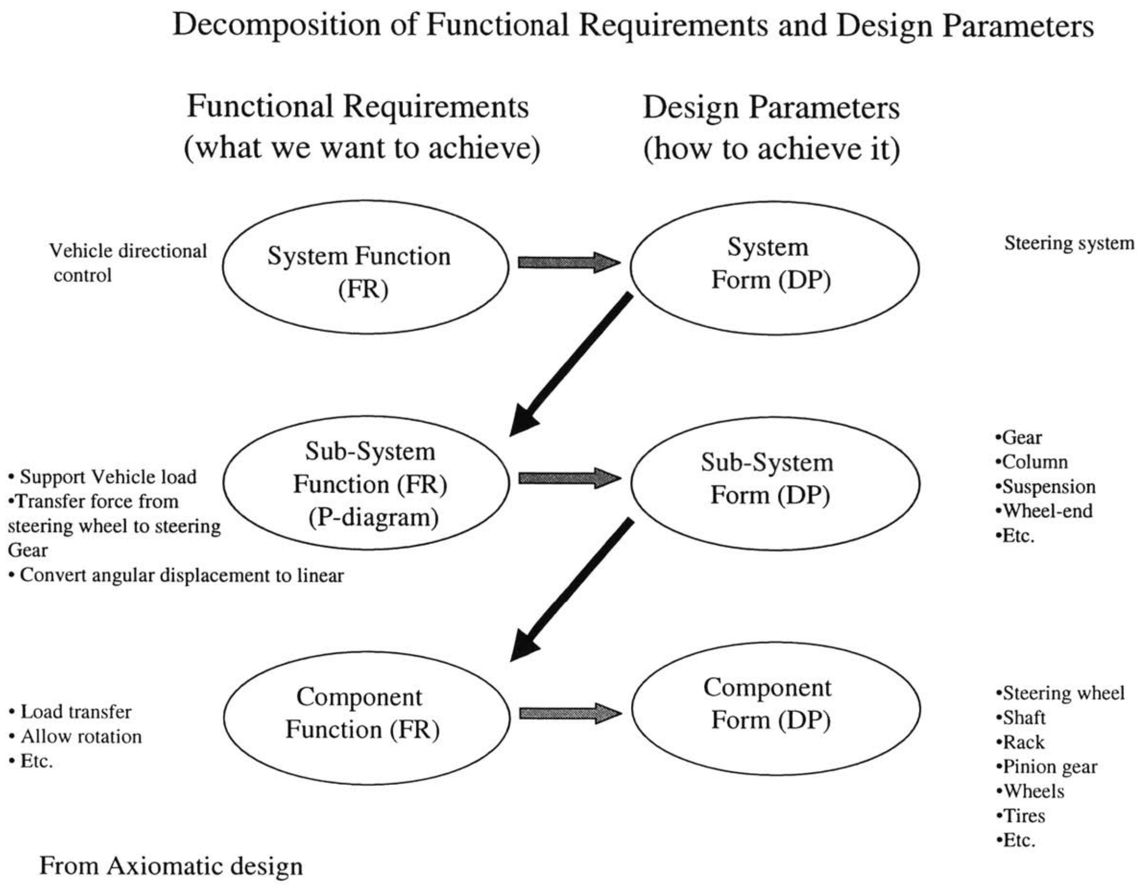
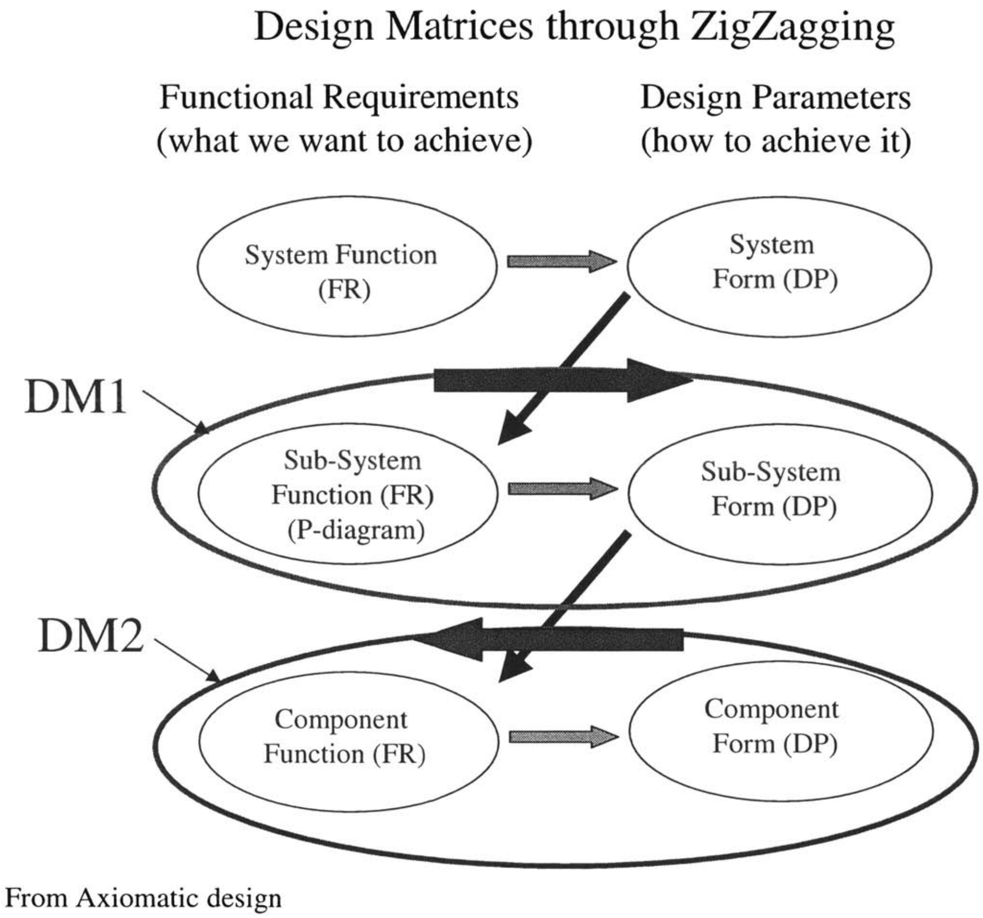


Figure 28: Decomposition of FRs and DPs

The design matrices, DM1 and DM2, were obtained from the zigzagging method as shown in Figure 29.



<u>Figure 29: Development of DM1 and DM2</u>

With DM1 and DM2 defined and then combined, Design Structure Matrices were developed in a manner described by steps 13 through 17 as shown in Figure 30.

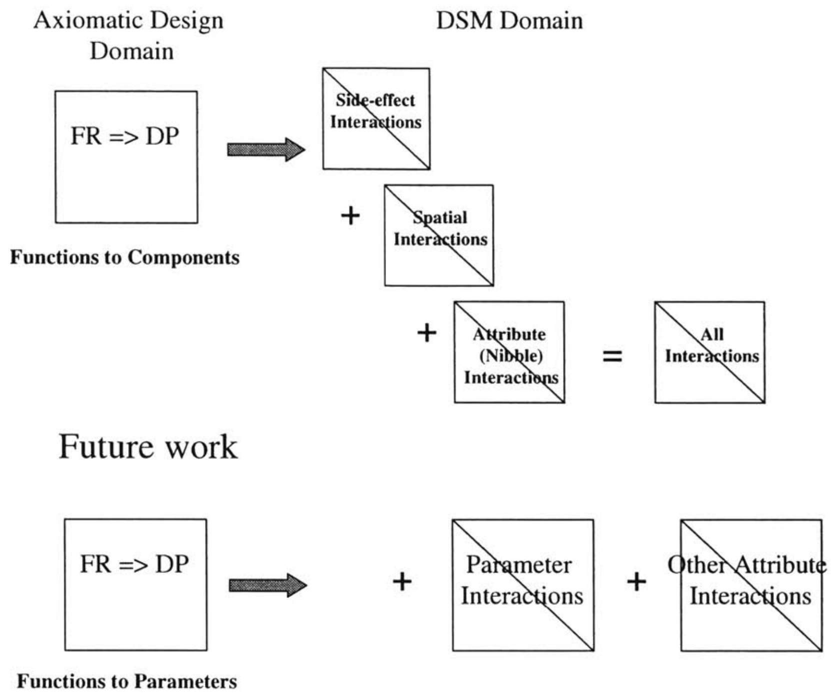


Figure 30: Axiomatic Design Domain and DSM Domain

5.2.1 Adding Matrices to Combine Types of Interactions

To combine different types of interactions and relationships in the system, matrix addition was used. Matrix addition allows us to maintain identification of types of interactions. For example, side-effect interactions from the DM were marked as ones (1), spatial interactions were marked two (2). A DSM was made for each interaction type. When the two matrices were added together, cells with ones in them indicated that the interaction was only a DM interaction. Cells with a two in them indicated only a spatial interaction. Cells with threes in them indicated both a DM interaction and a spatial interaction. Matrices were colored according to the type of interaction to aid in highlighting the interaction type.

5.2.2 Decomposition

As SUV's continue to evolve and more and more competitors enter the SUV marketplace, designers and architects look to major subsystems to provide distinction and uniqueness. Steering systems have been around for decades (centuries) in various forms of architecture, all with the same underlying function of directing or steering whatever vehicle to which the system belongs. The UXXX steering system is decomposed as follows:

- Needs Identification
- Problem Statement
- Function
- Form

5.2.3 Needs Identification

Just as styling and appearance are a need of some consumers, attributes associated with how something feels is also an underlying need. In the case of the SUV steering system the user needs to feel confident and in control of the vehicle as they interface with the steering system. The user also needs to feel that there is nothing wrong with the vehicle when interfacing with the system (e.g., vibrations or excessive play felt by the user at the steering system interface—steering wheel). In reflecting on underlying needs it is easy to regard only the user (consumer) as the entity that has needs. There are many stakeholders that need something from a steering system. The corporate entity represented by senior executives (also shareholders), need the steering system to contribute to overall corporate profitability. This may be accomplished by developing a steering system architecture that provides differentiating attributes to the overall vehicle such as best-in-class precision, feel, turning radius, efforts, etc., or through economies of scale where elements of the system are shared with other appropriate products. At the beginning of the UXXX program it was determined that critical stakeholder needs for maneuvering/handling attributes were not currently being met by the current product architecture. Improvements were sought in many areas of the vehicle including steering attributes.

5.2.4 Problem Statement

Based on interviews of engineers involved in the UXXX program the following problem statement can be inferred as direction during the steering system development:

System Problem Statement: Develop steering system with highest precision and lowest friction possible.

5.2.5 External Function

The external function of the steering (sub) system is to direct the vehicle (system) in a path intended by the user and to provide the ability of the user to determine the intended path. The steering system provides a user interface for control and connects the directing components to the vehicle and a surface of varying friction. The steering system provides vehicle steering input feedback.

5.2.6 Form

The form of the steering system consists of a round wheel for the user to grip, a series of shafts and joints, which meshes with a perpendicular steering gear or rack assembly. The rack assembly translates transversely and connects to a steering knuckle and hub, which in turn connect to the wheel/tire assembly. The steering system form also includes structure for attachment to vehicle frame and body. Figure 31 illustrates the scope of this research through form decomposition. In the context of this project, the automobile is level 0 of the architectural decomposition. The steering system is a subsystem of the automobile chassis system and we will refer to it as level 2 of the decomposition. In practice, the vehicle level is divided into body, electrical, chassis, powertrain and climate control systems. For the purposes of this project, the steering subsystem is the focus and is defined as a level 2 subsystem.

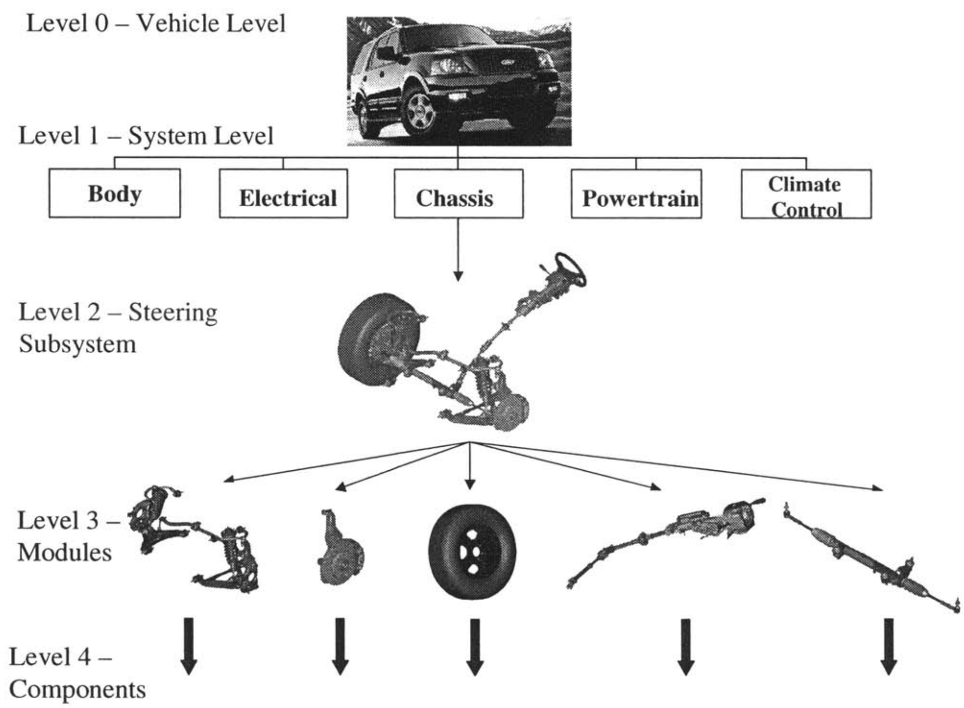


Figure 31: System Form Decomposition

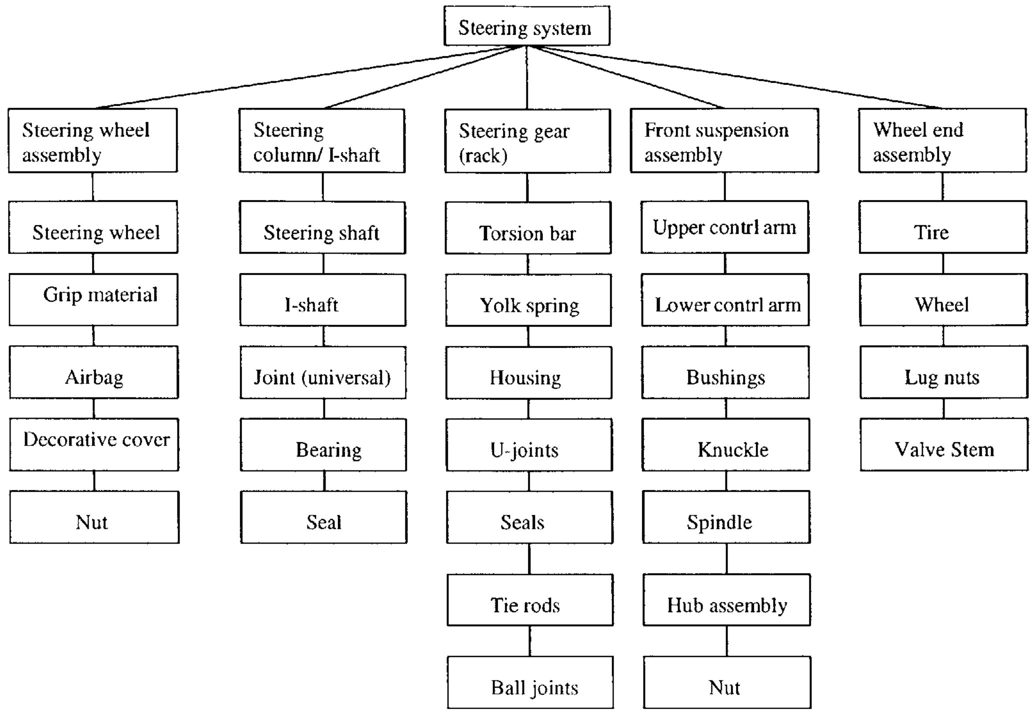


Figure 32: Steering System form decomposition

5.2.7 High Level Concept

The driver uses the steering wheel to maneuver the automobile. Based on the driver's input of torque (movement of the steering wheel) becomes converted into transverse forces within the steering gear that then provides directional inputs to the wheel/tire assemblies. Lateral forces offset from the axis of rotation of each of the front wheels cause pivoting about the knuckle's ball joints. This pivot movement of the tires, along with the tire's primary function of friction to the road surface, result in turning the automobile in the direction intended by the driver.

6.0 RESULTS AND ANALYSIS

Modeling the steering system using the requirements based and component based DSM methodologies provides interesting insights into the following areas:

- Analysis of physical system
- Organization Analysis
- Identifying and defining FRs and DPs
- DM analysis
- DM to DSM analysis
- Analysis of a combination of interactions and relationships

6.1 Analysis of Physical System

One method used to analyze interactions involved in Nibble was to construct a DSM documenting all the physical (spatial) interactions of the steering system (Figure 33). The matrix in Figure 33 is physical interaction DSM and was developed for an initial analysis of the system for the purpose of understanding the interactions of components and sub-assemblies within the steering system. Further matrices were developed and analyzed using the composite list of DPs (combined DM and resulting DSM) and are discussed in section 6.6.

The initial order of components listed in this matrix parallels system decomposition. The steering system was simply decomposed to level 4 and physical interactions between system components were indicated in the matrix, starting with the steering wheel and progressing through the system to the wheels and tires. Additional components where interactions were considered important for the analysis were added to the end of the list. Component sequencing or partitioning occurred later in the analysis.

This analysis yielded not much more than simply a graphical view of the interactions. When partitioned we can see how the chassis development team may be logically organized in order to minimize interfacing activities. It is always easier to interface with one's self or within the engineer's immediate design group rather than across department boundaries Figure 34 is the partitioned spatial DSM developed as an initial analysis of the steering system from the DM2 (components) perspective (see section 5.2). Partitioning rearranges the components and subassemblies to be close to the diagonal, indicating that relationships exist between components grouped close together. In this case the relationships are physical interactions or connections. The solid blue boxes depict the current engineering work structure within the steering system. The dotted line boxes drawn around grouped components show relationships and suggest possible organization of engineering effort. The fewer the number of shared interactions across department boundaries the better as each interaction represents an interface where requirements need to be communicated and validated. The partitioning analysis moved the positions of the following components/ subassemblies within the DSM:

59. Cross Car Beam
58. Dash Panel
31. Input Shaft
29. T-Bar
30. Valve Sleeve
57. Frame
32. Upper Control Arm
36. Steering Knuckle
33. Lower Control Arm

Frame, Cross-Car Beam and Dash Panel are moved when partitioning because they were added to the list of components after all others and the partitioning algorithm simply rearranged them to be in better proximity to components they physically interact with. The fact that partitioning the DSM located them within subassembly groups shows the power of the DSM partitioning algorithm. Since these are interfacing components outside the system boundaries they are not included within the DSM subsystem boundaries. The DSM, in this case provides information about which components and subsystems interface with these important out-of-boundary components.

6.2 Organization Analysis

The matrix in Figure 34 is very similar to the current organization at Ford Motor Company as seen by the difference between the solid blue boxes and the dotted line boxes. The steering knuckle is the only steering system component that was moved from one organizational department to another after partitioning the DSM. As Ford Motor Company is presently organized; the steering knuckle is designed and released by the brake (wheel-end as defined by this thesis) group. The DSM suggests that suspension system ownership may be more logical based on physical (spatial) interactions. The author found evidence of confusion of roles with respect to the steering knuckle when interviewing engineers, lending credibility to what the DSM shows. Some suspension engineers questioned why the brake-engineering group engineered the knuckle. In reality, responsibility for the steering knuckle could go either way provided management of the interfaces is executed well.

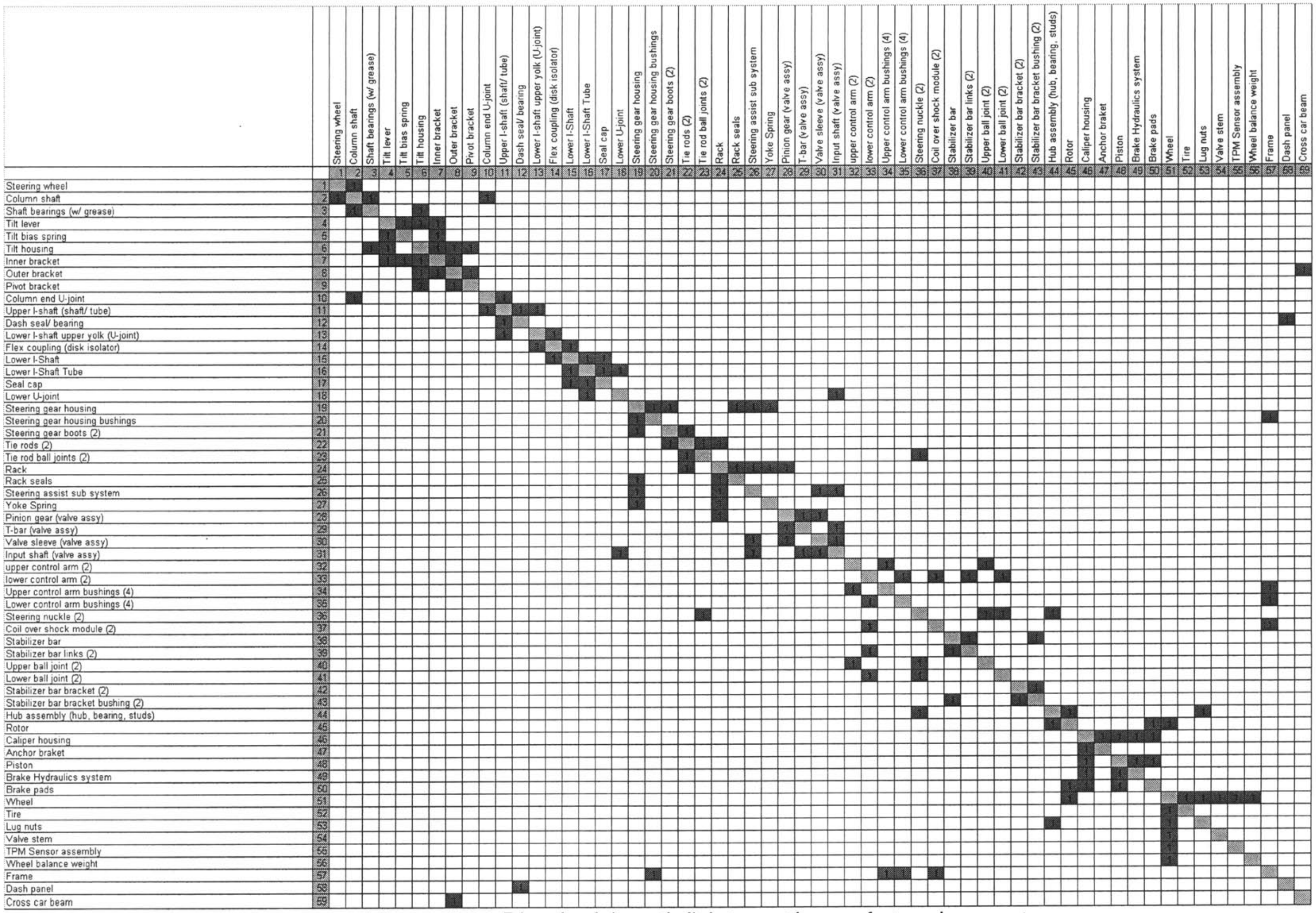


Figure 33: Physical (spatial) interactions of steering system

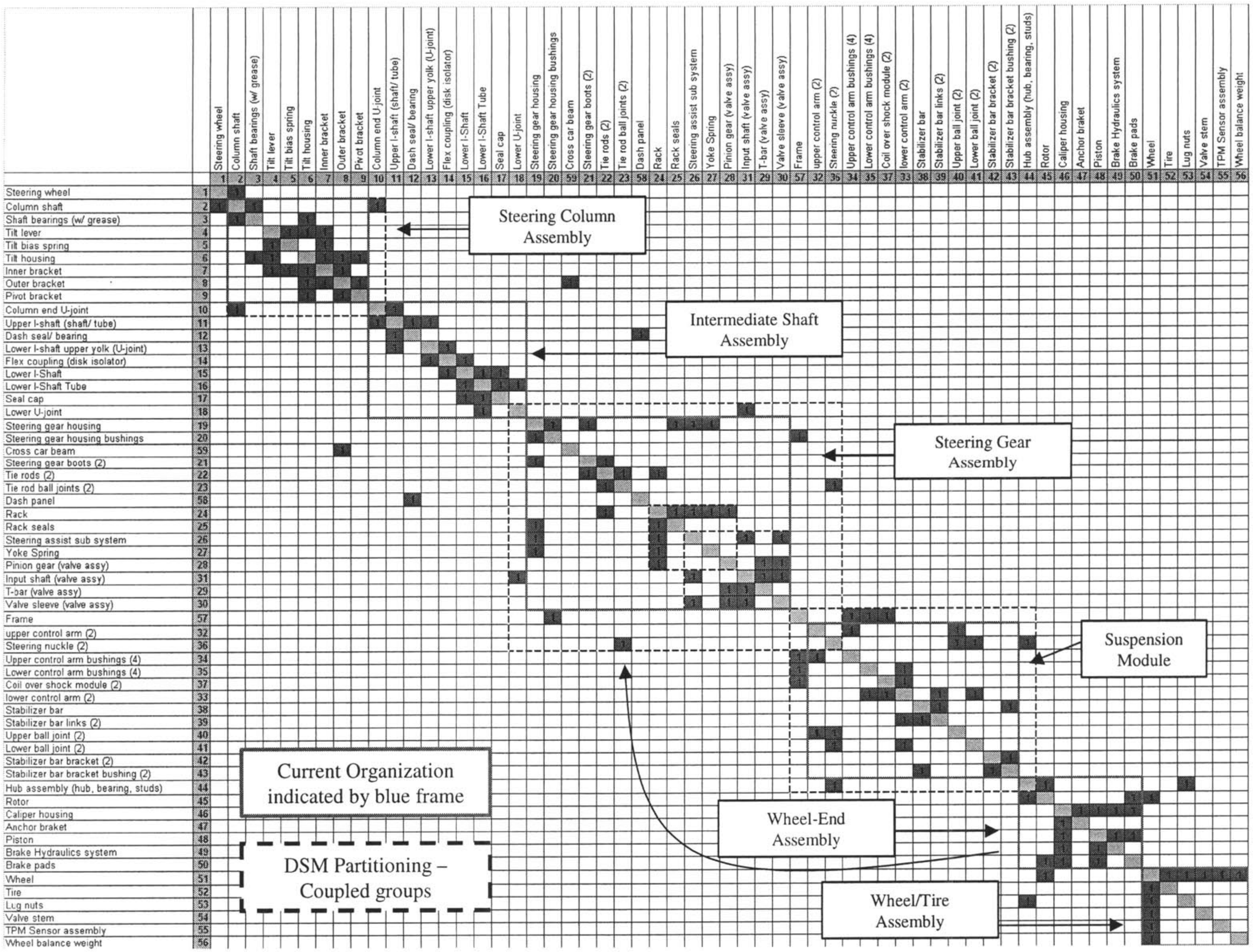


Figure 34: Partitioned Physical Interaction DSM

6.3 Identifying and Defining FRs and DPs

As discussed in the methods section, there were two approaches to developing and synthesizing FRs and DPs. The first method led to DM1 where Functional Requirements were obtained directly from subsystem P-diagrams. The second approach led to DM2 where after the steering system was decomposed to what is called level 4, the function of each component was then determined through discussions with appropriate engineers and technical experts.

DM1 and DM2 were compared and synthesized resulting in a combined DM. Insights were discovered when comparing the two approaches. The author's initial thinking was that DM1 would represent a higher order of decomposition of FRs and DPs than DM2. The thinking was that DM2 would be a lower level of decomposition since the FRs were developed by reflecting on the function of each component after the system was decomposed to level 4. This thinking was proven incorrect. The development of DM1 led to DPs at lower levels of decomposition than the DPs included in DM2. By combining and synthesizing DM1 and DM2 we arrive at a more complete list of FRs and DPs. Some of the insights obtained include:

- Better definition of tire FRs and DPs – The DM2 approach described the tire with one FR and one DP. The DM1 approach listed four FRs, which led to the definition of four DPs. DM2 assigned only one FR to the tire. DM1 provided a better definition of functional requirements and design parameters and at a lower level of decomposition than DM2.

- Better definition of wheel FRs and DPs – Similar to that of the tire, DM1 represents the functional requirements and design parameters more clearly and at a lower level than DM2 in some cases.
- It is important to analyze the system from both the functional perspective and component perspective and then build a composite list of FRs and DPs. The DM results were found to be more meaningful when working from both perspectives. The P-diagram approach demands a functional approach to decomposition. Some type of form, either a component or combination of components, must support each function.
- Better definition of steering wheel – The DM1 approach decomposed the steering wheel to a more meaningful level, separating the functions of locating steering wheel to column shaft from the function of transferring torque from the wheel to the column shaft.
- Better understanding of steering gear – the rack and pinion is really one DP. The pinion or rack cannot function separately. Both components are required to produce the DP of gear ratio.
- DM2 decomposed some system elements to levels that didn't make sense, for example, the rack gear and pinion gear were decomposed as separate components, which they are, but functionally they cannot be separated. In this case the synthesized DM considers the rack and pinion gear as a single element.

With FRs and DPs synthesized into a final combined list, a DM was developed. Figure 35 shows the combined DM with the FRs mapped to each DP on the diagonal. Other markings in the DM represent "side effects" on the FR by other DPs. According to Suh's Independence Axiom, above diagonal interactions indicate a coupled design and is unacceptable. However, to improve analysis of interactions, the full matrix was transformed mathematically using Eric McGill's matrix transformation algorithm to optimize the matrix (Figure 36).

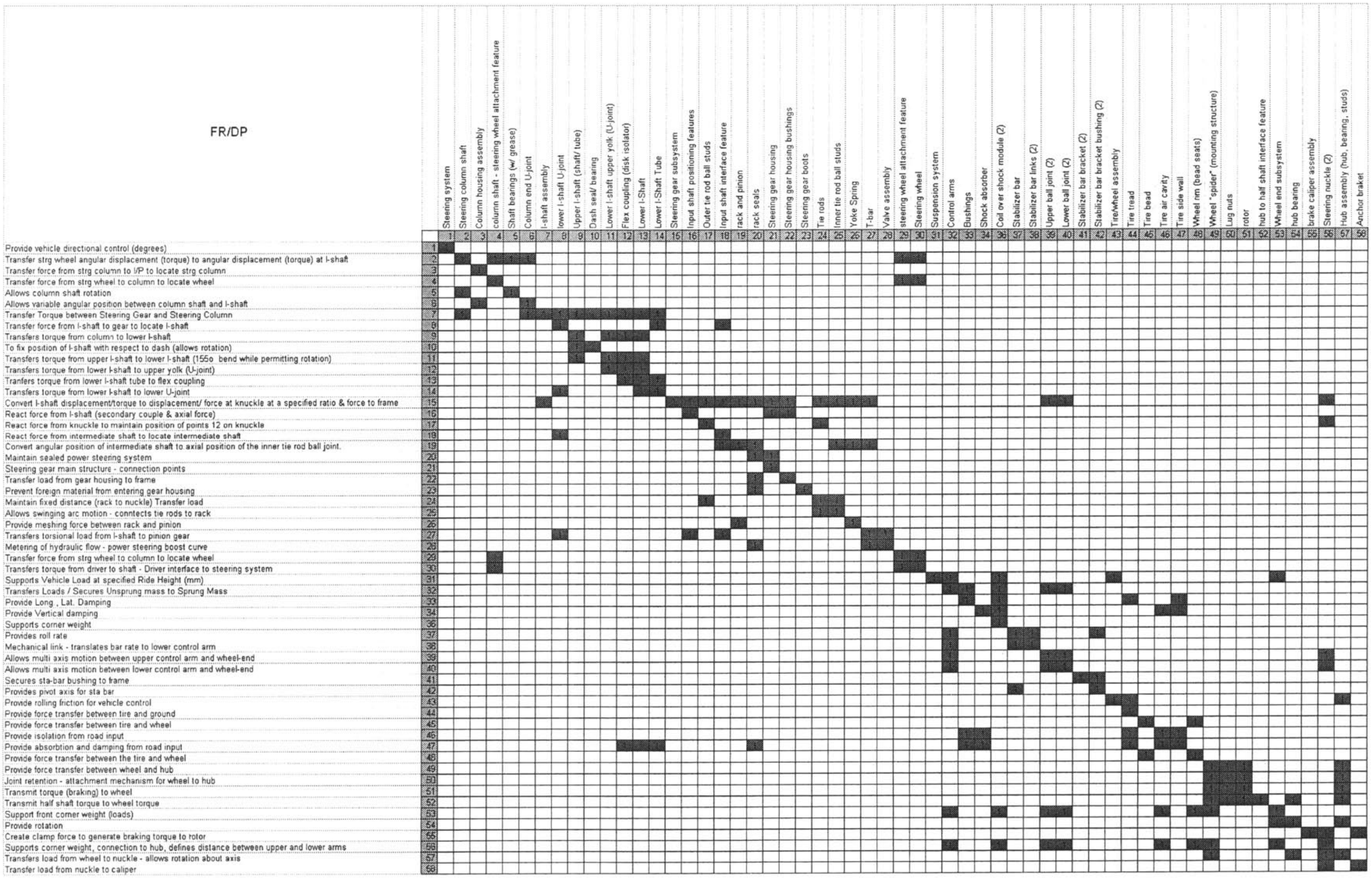


Figure 35: Combined DM

6.4 DM Analysis

The DM shown in Figure 36 could not be transformed to a completely lower triangular or diagonal matrix. Several interactions fall above the diagonal in the upper triangle. This indicates that there are coupled areas within the design of the steering system as a whole. There are two areas of concern in the design according to the Independence Axiom. These areas are considered coupled and are highlighted in Figure 37 and Figure 38.

The first area highlighted by the Independence Axiom shows the coupled nature of the steering column and I-shaft subsystems. The second area highlighted shows that the function of carrying the corner load of the vehicle is very coupled between suspension DPs, Wheel-end DPs and Wheel DPs.

In Chapter 4 Suh was quoted as saying that "any matrix can be mathematically transformed into a diagonal matrix." It was very difficult to prove this statement as the system studied here still had many upper-triangular interactions even after mathematically transforming the matrix. His theories would say that design actions are necessary to "undo" the coupled relationships. Perhaps this is the case, but the fact that the subject system is pre-existing (not a clean sheet design) and considering all the constraints may lead to an analysis that there will always be upper triangular interactions in this system.

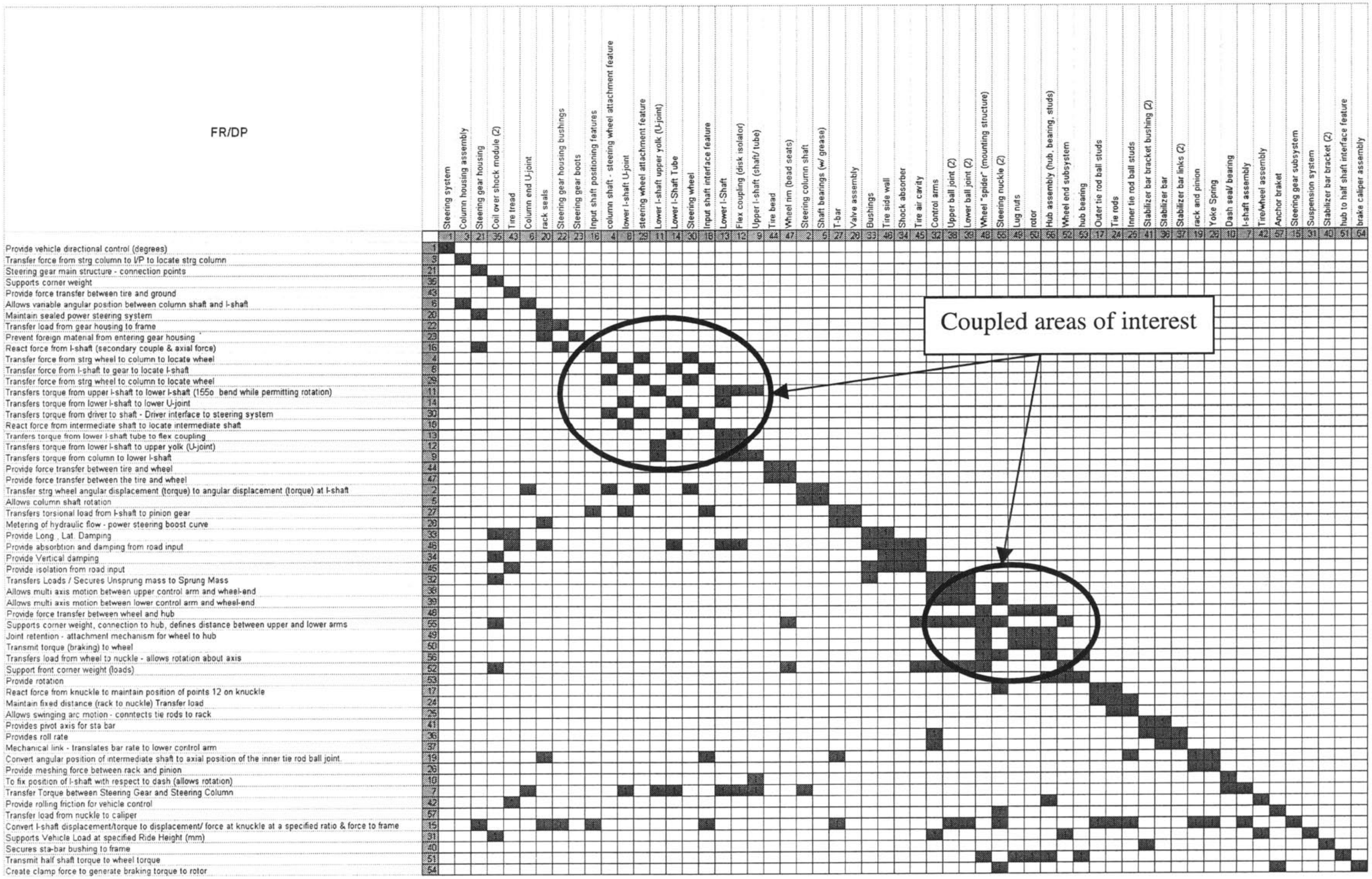


Figure 36: Combined DM – Partitioned

FR/DP	FR	column shaft - steering wheel attachment feature	lower I-shaft U-joint	steering wheel attachment feature	Lower I-shaft upper yolk (U-joint)	Lower I-Shaft Tube	Steering wheel	Input shaft interface feature	Lower I-Shaft	Flex coupling (disk isolator)	Upper I-shaft (shaft/ tube)
DP		4	8	29	11	14	30	18	13	12	9
Transfer force from strg wheel to column to locate wheel	4	1		1			1				
Transfer force from I-shaft to gear to locate I-shaft	8		1			1		1			
Transfer force from strg wheel to column to locate wheel	29	1		1			1				
Transfers torque from upper I-shaft to lower I-shaft (155o bend while permitting rotation)	11				1				1	1	1
Transfers torque from lower I-shaft to lower U-joint	14		1			1			1		
Transfers torque from driver to shaft - Driver interface to steering system	30	1		1			1				
React force from intermediate shaft to locate intermediate shaft	18		1					1			
Tranfers torque from lower I-shaft tube to flex coupling	13					1			1	1	
Transfers torque from lower I-shaft to upper yolk (U-joint)	12				1				1	1	
Transfers torque from column to lower I-shaft	9				1				1	1	1

Figure 37: Coupled Area 1

FR/DP	FR	Control arms	Upper ball joint (2)	Lower ball joint (2)	Wheel "spider" (mounting structure)	Steering nuckle (2)	Lug nuts	rotor	Hub assembly (hub, bearing, studs	Wheel end subsystem	hub bearing
DP		32	38	39	48	55	49	50	56	52	53
Transfers Loads / Secures Unsprung mass to Sprung Mass	32	1	1	1							
Allows multi axis motion between upper control arm and wheel-end	38	1	1	1		1					
Allows multi axis motion between lower control arm and wheel-end	39	1	1	1		1					
Provide force transfer between wheel and hub	48				1		1	1	1		
Supports corner weight, connection to hub, defines distance between upper and lower arms	55	1	1	1	1	1				1	
Joint retention - attachment mechanism for wheel to hub	49				1		1	1	1		
Transmit torque (braking) to wheel	50				1		1	1	1		
Transfers load from wheel to nuckle - allows rotation about axis	56				1	1			1		1
Support front corner weight (loads)	52	1	1	1	1					1	
Provide rotation	53								1	1	1

Figure 38: Coupled Area 2

Coupled area 1 delivers the function of transferring torque between the driver and the steering gear. Coupled are 2 provides functions of supporting corner weight of vehicle. Axiomatic design would suggest that all coupled interactions need to be eliminated. Upon analyzing all functional requirements and constraints placed on the design of the steering system, we suggest that elimination of all coupled interactions is an oversimplification of the steering system. Appendix 5 provides a listing of steering system constraints.

6.5 DM to DSM Transformation

The Axiomatic Design's Design Matrix (Matrix 1 in Appendix 4) was transformed into a DSM by using the diagonal interactions as input variables. The resulting matrix is a prediction of interactions (both spatial interactions and side-effects) based on system requirements. Compiling system requirements from existing P-diagrams and determining the system elements that delivered the requirement or function arrived at these "predictions." As far as we can tell, the "predicted" interactions are congruent with the current knowledge of the system interactions.

It is difficult to say if the resulting DSM "tells the story of the case" because knowledge obtained during the case influenced the interactions indicated in the matrices. It was nearly impossible to completely separate knowledge and experience from the desire to build a "predictive" model. That is to say, if we were starting completely from a clean slate, all interactions would have been predictive. In this case, the system already exists and we were using the matrix methods to go back in time to see if predictions agree with our knowledge of the system, as it exists.

Transforming the DM to the DSM seems to work but to say that the interactions are predictive may be a stretch because of the influence of knowledge and experience on the development of the matrix.

6.6 Analysis of a Combination of Interactions and Relationships

In order to analyze the combination of interactions and relationships, several matrices were compared. The following interactions, thus matrices, were compared through addition:

- DSM – Transformed from DM where interactions were developed from a functional requirement point of view
- Spatial interactions – what touches what
- Nibble interactions – what design parameters affect Nibble (see section 5.1)

Figure 39 below represents a comparison of these matrices where Matrix 3 is the resulting requirements based DSM developed from Axiomatic Design's Design Matrix (DM), Matrix 4 is a component based DSM of spatial interactions and Matrix 6 is a DSM that records the relationships of components to the error state of Nibble. Matrices 5, 7 and 9 are the resulting comparison matrices that show how the interactions relate to each other (See Appendix 4 for full size matrices).

Matrix 5 is the sum of Matrix 3 and 4. Cells marked with the number 1 indicate interactions from Matrix 3 (requirements based). Cells marked with the number 2 indicate interactions from Matrix 4 (component based. In some cases, the interaction is both spatial (component based) and a "side effect" of functional requirements (requirement based). When this occurs, the cell is marked with a 3.

Matrix 7 is the sum of Matrix 5 and 6. Cells marked with a 1 indicate a relationship between Nibble and the design parameter. Cells marked with a 2 indicate an interaction from Matrix 5. Cells marked with a 3 indicate a combined reaction of requirements based, component based and Nibble based.

Matrix 9 is the partitioned version of Matrix 7. It shows a dense Nibble block and provides a single source of documentation of all studied interactions within the steering system with respect to steering Nibble. There are other interactions that occur in the system that will be the subject of future work (see Future Work section 8.0).

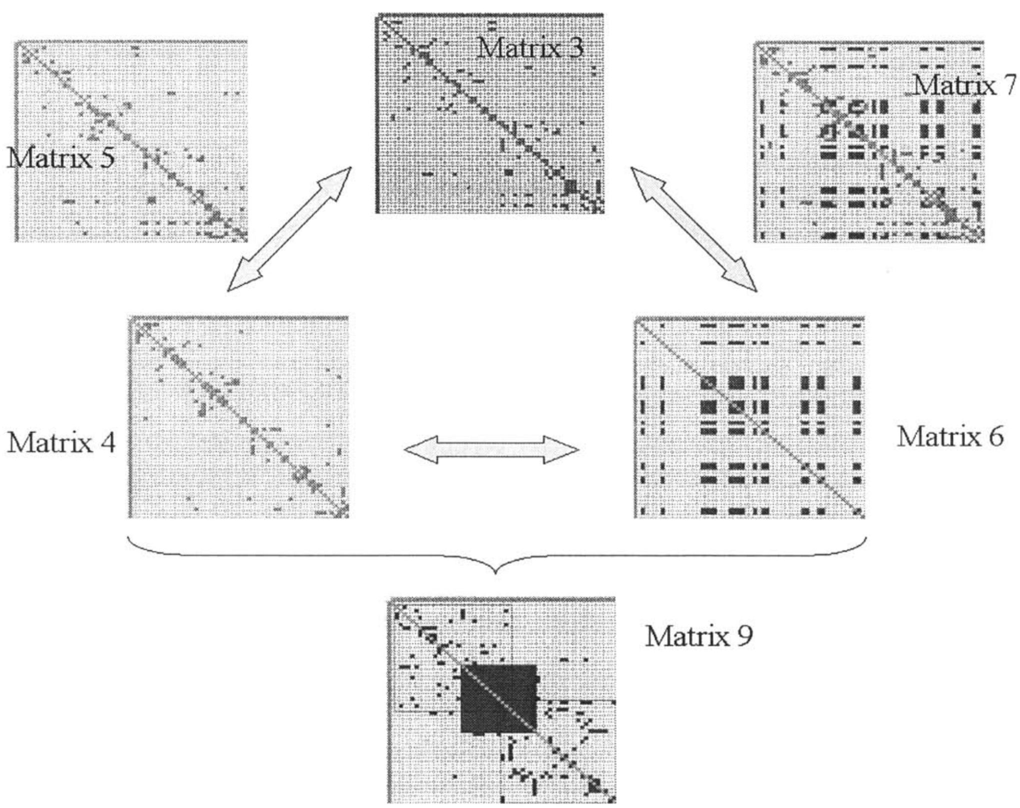


Figure 39: Comparison of Matrices

Matrix 9 shows the coupled nature of the steering system with respect to Nibble. To analyze Matrix 9 two methods were employed, 1) execute Qi Hommes DSM macro to determine coupled areas and, 2) manipulate sequence of components using Eric McGill's matrix macro. When executing Qi Hommes (Dong 1998) matrix partitioning algorithm we see that the entire matrix is coupled. Only DP 1, Steering System, is considered a parallel or uncoupled system element according to the analysis. The reason for the uncoupled nature of the steering system from the rest of the system elements and components is due to how the author defined interactions at the system level. The fifty-seven elements that make up the steering system include the hierarchy of system, subsystem, components and features (parameters). Interactions under the highest level of the system, element 1 – Steering System, simply were not marked. So, the analysis that 1 is not coupled with the rest of the elements can be ignored. According to the algorithm for analyzing DSMs, partitioning or rearranging system elements is meaningless as they are all coupled.

Matrix 9 in Figure 39 shows a solid block of interactions. This was achieved by manually manipulating the sequence of DPs where it made sense to do so. With the understanding that all elements are coupled and the organization of elements into a "Nibble Block" we can document what elements most impact Nibble and map other important interactions in the system. With the mapping complete, the DSM can be a tool for engineers to visualize the interactions they need to deal with when impacting a certain component or design parameter. Perhaps this is the most useful aspect of the DSM models. When designing or redesigning a specific component, the DSM tool will help the component engineer to be more of a systems engineer, it will facilitate the thought process and increase the likelihood of considering the affect of design changes of one component on other components and thus system attributes.

7.0 DISCUSSION

In this section we will discuss important findings within the scope of the research and further discuss insights of the case study. It is also important to discuss what went well or what didn't go so well with respect to the tools and methods used in this research.

7.1 Questions from the Case

The case presented earlier discussed some of the difficulties and perspectives during the development phases of an all-new SUV. The case also discussed the costs associated with some of the decisions and personalities involved in the development of steering system attributes. One of the adverse effects of these decisions was higher component costs, higher engineering costs, poor warranty and low customer satisfaction. After reviewing the case some questions arose and were stated at the end of section 3 and are repeated here:

- How can "Nibble" be prevented?
- Can steering system attributes be executed without error states?
- What organizational aspects allowed this to happen?
- Does the direction to remove as much friction and compliance as possible make sense... Can it be shown in the matrix methodology that it doesn't?
- Can story in case be found in matrices?

How can "Nibble" be prevented?

This question is really a question about balancing tradeoffs, not a technical question about how to solve or prevent Nibble. Giving up other attributes such as precision and response can technically solve Nibble relatively easily. A re-circulating ball type steering gear typically provides enough compliance in the gear to avoid Nibble but does not provide the precision and other attributes desired by customers.

Other thoughts on preventing Nibble include design changes and innovations:

- Reduced king-pin offset design. This idea was discussed with a suspension system integration engineer. The king-pin is the imaginary line through the upper and lower ball joints. With the understanding obtained from matrix analysis of interactions it seems reasonable to believe that to be more robust to normal force variations of the tire/wheel (T1H and imbalance), a reduced king-pin offset may reduce the effect of T1H and imbalance.
- Drive-by-wire steering. Drive-by-wire steering would eliminate the spatial interactions or path between the gear and the steering wheel where vibration is transmitted. Drive-by-wire has been experimented with but has not yet been developed into a viable production system. One of the reasons why is that customer's desire a certain amount of feedback and current drive-by-wire steering systems feel too "artificial". It will be interesting to see future developments of drive-by-wire technology.

Can steering system attributes be executed without error states?

The case and the events following the case lead us to believe that steering attributes will always be traded, at least in a small way, with error states. As shown in Appendix 2, many design iterations have taken place and some since then, all changes had some impact on attributes. The true challenge is to understand clearly what is important to the customer and balance the attributes in a way the makes sense, given the constraints. In the case of UXXX, it was discovered after launch, that real customers valued a smooth ride (no vibration) over precision and responsiveness (see Bagley, et al. (2003)].

What organizational aspects allowed this to happen?

It can only be speculated that a lack of discipline in adhering to existing process allowed steering system targets to evolve throughout the development phases.

Another organizational aspect is the relative strength of the vehicle's chief architect (Chief Program Engineer) and the existing knowledge of the risk of Nibble given the other attribute requirements. In the case of the UXXX, the Chief Engineer was not directing the attributes and was overpowered by a higher-level executive claiming to know what the customer wanted in steering attributes. It is reported that the top Asian automobile manufacturers give far more authority to Chief Program Engineers than Ford does and their tenure as Chief Engineers lasts much longer. Perhaps this is an important organizational factor that allowed Nibble to become the problem that it was.

Another element is the "over the wall" approach to vehicle development. At Ford the mentality has been that the job of developing a vehicle is Product Development's job and the time comes it will be handed over to Manufacturing to produce it. This was seen in the case of UXXX where during its "hand off" to manufacturing, Nibble became a hot issue as it was considered unacceptable to manufacturing. At this stage in the PD process, manufacturing tends to have program management leverage because they have a strong influence over acceptability of the product and timing of launch. Because of this leverage, steering targets (and other targets) set by the PD executive became secondary to a solution to the Nibble problem.

Does the direction to remove as much friction and compliance as possible make sense... Can it be shown in the matrix methodology that it doesn't?

We would argue that the direction given to "remove as much friction and compliance from the steering system" was not good direction. This direction does not meet the definition of a good engineering requirement. It is vague, is not data driven and provides no clear measurable metric to determine success. As a result, steering system attribute development became a trial and error process.

The matrix method does not show that removing as much friction and compliance is bad direction. The method shows the interactions in the system that needs to be considered during the product development process. It does not present parameter outputs given certain inputs. The matrices capture and document knowledge. The matrices don't necessarily tell the story of how Nibble emerged as a concern but show a picture of the important parameter interactions that cause Nibble to occur.

This research shows how matrices of different types (requirements based, spatial and attribute based) can be added and compared to build a composite of all types of interactions. The composite matrix can be used to prevent Nibble in the future by providing engineers with a "picture" of the interactions within the steering system that impact Nibble. Understanding the interactions along with other CAE tools can help to ensure better attributes in the future.

7.2 Other Topics for Discussion

Other important topics will be discussed in the section as follows:

- What was learned from each method (DM vs. DSM)?
- Is Axiomatic design appropriate for steering system design?
- Using technical models (CAE)

7.2.1 What was learned from each method (DM vs. DSM)?

The development of the DM gave good insight and understanding of the subject system. Analyzing the system from a customer requirements perspective is an important method for developing and documenting system interactions. In this work two methods were followed in developing a list of system design parameters (DPs). The first method was to decompose the system to its components and then reflect back to the function of each component. The second method was to start with system requirements found in P-diagrams (developed by system experts) and then decide what design parameter (DP) delivered the function. Following both methods and then synthesizing the two lists of DPs into one common list is a very important discovery in this research.

Another important discovery was the development of a method for comparing different types of system interactions. By creating multiple DSMs (spatial, Nibble, requirements based), we were able to analyze the interactions separately. We were able to compare how the different interactions related to each other by matrix addition. With all interactions on one matrix it was interesting to see that the entire matrix was coupled.

7.2.2 Is Axiomatic design appropriate for steering system design?

With a clean sheet design opportunity Axiomatic Design would be more appropriate for steering system design. In this case we were looking for ways to understand and improve the attributes of a pre-existing steering system. Axiomatic Design has value in this case for system analysis. Axiomatic Design was and important part of developing functional requirement understanding and generating the list of system design parameters.

Nam Suh (MIT) and other Axiomatic Design researchers recently worked with Ford engineers to develop an Axiomatic Designed steering system proposal. The activity was unable to successfully satisfy all the constraints of the system. Several interesting ideas were presented and discussed and we conclude that their theories are important to consider for steering system design when constraints allow. The current design can be evaluated with respect to Suh's theories to determine where couplings can be removed without violating critical constraints.

7.2.3 Using technical models (CAE)

The matrix method cannot alone provide design direction. The understanding achieved through the matrix method may be used to develop working CAE models or validate existing ones (see Future Work Chapter 8.0). The following section discusses one such CAE tool developed for Nibble.

7.3 Development of CAE for Nibble

Since the development program of UXXX, more CAE tools have been developed and improved for handling error states such as Nibble. Ford Motor Company now analytically assesses risk for Nibble mainly using the VSIGN software, a Ford internally developed Vehicle NVH simulation code. Benchmarking activities are being carried on to verify the potential of commercially available packages, but none of those at the moment offer the same capabilities. The acronym VSIGN stands for Vehicle System Integrated GUI for NVH. VSIGN calculates separately the force and the vehicle sensitivity bringing together data from a number of sources and compiling them into one integrated model. Automatic standard events and processes are tailored to simulate Ford standard tests, including the Shake and Nibble test. The acoustic model is completely integrated with the vibration model.

CAE modeling requires a considerable amount of geometry information and component test data, for example steering rack damping, elastomer characteristics, and T-bar torsional stiffness. Along with component data it is necessary to have a good understanding of body and frame assembly tolerances. This may extend to tolerances affecting the suspension. If the suspension connect points are not at their nominal positions then suspension bushings will be subject to unexpected pre-loads, which may alter their stiffness. Tire-wheel assembly forces are required to determine the CAE load cases [Bagley, et al. (2003)].

8.0 FUTURE WORK

There are many areas of work that were not feasible to be completed within the scope this research. Areas of additional work are discussed in the following sections:

- Compare DSM Interactions with Existing CAE Tools
- Add Other Attribute Interactions to DSM Models
- Define Roles and Responsibilities of Subsystem Architects (Subsystem Integrators)

8.1 Compare DSM Interactions With Existing CAE Tools

Validate VSIGN interactions and DSM interactions by comparing to each other. VSIGN may validate the DSM models and the DSMs may validate VSIGN. The work was not done and should be the subject of future work. With CAE tools we can go beyond what the DSMs tell us and develop design direction without building expensive prototypes.

8.2 Add Other Attribute Interactions to DSM Models

Other steering attributes including efforts, precision and response were not included in the final DSM. The addition of these relationships should provide valuable insights for the subsystem architect (integrator) to help manage interfaces and to balance tradeoffs. It would be important to analyze and document the interactions of other attributes. The current thinking and undocumented knowledge is that many attributes conflict with the error states. For example, through interviews, engineers have stated that the system must trade steering precision and response for Nibble insensitivity.

With a better understanding and documentation of the interactions within the steering system, current CAE tools can be validated and analytical DOEs can be completed to determine sensitivities within the system and their effects on the attributes.

8.3 Define Roles and Responsibilities of Subsystem Architects

As suggested in conclusions and recommendations, the steering subsystem needs an architect, an individual responsible for delivering the objectives of the system. There are too many important requirements and constraints to leave it up to multiple functional areas and to depend on them to communicate and manage the interfaces themselves. The subsystem architect can be called a Chassis Systems Integrator. Their primary responsibilities should be focused on interfaces and interactions, not components. Future work should include a complete definition of the chassis systems integrator's roles and responsibilities.

Similar roles exist in other organizations within Ford Motor Company. For example, Body engineering has incorporated a Closures Systems Integrator (CSI) and has comprehensively defined their roles and responsibilities. The Closures SI is responsible for the system level requirements and interactions, not the engineering of components.

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

- The essence and challenge of systems engineering is to understand the system interactions/ interfaces and to manage them well.
- Nibble is a systemic issue, not a problem with tires/ wheels or steering gear or any particular component.
- The matrix methods do illustrate and document the interactions of the steering system and agree with the research case study. The matrix methods do not reveal what action to take to resolve nibble. The matrix methods indicate only that there is or is not an interaction and how the design parameters relate to each other (coupled or parallel). Other methods, physical and analytical (CAE) testing needs to be done to determine what action to take. The matrix methods are a good starting point for building CAE tools.
- Nibble seems to be more of an organizational problem than a technical problem. The product development process was not followed in a disciplined enough manner to keep targets from changing late in the program and to decouple strong personalities from the process.
- Steering system targets were not aligned with real customer requirements. The feedback loop was not closed to verify that steering targets were congruent with what the "customers" value.
- From the case is it clear that strong personalities within an organization can have a profound impact on the resulting performance of the system.

- Optimization of components does not mean the system will be optimized...just expensive.
- When developing the requirements based DM, it was difficult separating current knowledge of system interactions in order to arrive at a purely predictive model.
- The difference between a component engineer and a system integrator is their focus. The component engineer's focus and responsibility is the design parameter (DP) as expressed by the component based DSM headings (first column, first row). The system integrator is responsible for interactions, or markings within the matrix. The component engineer should develop the capability of thinking like and integrator and the integrator should understand the design parameters.

9.2 Recommendations

- Define role of SI for Attributes. Vehicle Dynamics is closest we have to Attribute Integrator. Ford does have a Chassis Systems Integrator but he works for the suspension manager and tends to be focused on suspension components and interactions rather than chassis interactions. The suspension SI position seems disconnected from managing interfaces as discussed in section 4.5 (Managing interfaces) and bogged down in component design issues. The author recommends that the chassis SI report to the chassis chief functional engineer rather than the suspension manager.
- Add requirement for vehicle to be insensitive to a reasonable level of (reasonable for cost) wheel-end non-uniformity. The requirement would be in the form of a

System Design Specification (SDS). The incorporation of a new requirement at a system level is one step toward documenting system knowledge and continuous improvement to the vehicle design requirements.

- An effort needs to be undertaken to decouple the personalities from product development process by being more process disciplined and data driven.
- Use knowledge of interactions from matrix methods to validate and improve upon current CAE tools. A comprehensive DOE to determine main contributing factors in the system should follow CAE validation.

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11.0 APPENDICES

11.1 Appendix 1 – Nibble Case Study Interview Subjects

The Nibble case study interviews:

- Wheel/tire design engineering supervisor (Kim Steele)
- Wheel/tire design engineer (Matt Bagley)
- Tire technical specialist (Jerry Metters)
- Steering gear design engineer (Don Mattern)
- Steering column design engineer (Kasandra Flemming)
- Steering I-shaft design engineer (Sudak Kesamneni)
- Steering system technical specialist (Tim Oferle)
- Suspension systems engineer (Jason Sterly)
- Suspension technical specialist (Steve Allen)
- Vehicle dynamics manager (Mike Liubakka)
- Vehicle dynamics supervisor (James Radcliffe)
- Vehicle dynamics engineers (Dave Rieche, Ed Barretto)
- Wheel suppliers
- Tire suppliers

11.2 Appendix 2 – Nibble Case Tire/Wheel Changes

- Wheel pilot bore – five iterations of pilot bore diameter configurations and tolerances were implemented. After each change, the supplier was instructed to store previous versions of each wheel for future potential use. Over 33,000 wheels were set aside to await a future decision to use. The following wheel changes were made leading up to launch:
    1. Changed pilot bore configuration to off-center
    2. Reduced pilot bore nominal diameter by 0.1 mm
    3. Reduced pilot bore diameter tolerance
    4. Changed pilot bore configuration back to on-center
    5. Reduced pilot bore diameter tolerance again

- Tire force variation and imbalance specifications were tightened to best in class (BIC) standards.
- Wheel/ tire assembly balance – balance specifications in the assembly plant were reduced to equal specifications placed on smaller car assemblies weighing much less. Note: The UXXX tire and wheel assembly weighs about 50% more than typical car wheel & tire assemblies.
- Restricted usage of "ground" tires - tire manufactures typically grind the tread at the shoulder on a percentage of their production to meet OEM force variation (R1H) requirements. During this restriction period, one major supplier stored over 20,000 tires that had been lightly ground.

11.3 Appendix 3 – Changes to Reduce System Sensitivity

Product configuration prior and post Job #1:

- The steering T-bar (torsion bar) at 1PP was 16 in-oz
- Reduced to 14 in-oz at beginning of Continuous Build
- Reduced to 13.25 in-oz later during Continuous Build
- 90 days after job #1, the steering rack ratio was reduced
- Wheel pilot bore diameter was reduced to a minimum gap (wheel to hub) of only 0.03 mm
- Corrosion testing to confirm that the tight pilot bore didn't cause a corrosion concern was completed after job #1 and lead to management's decision to authorize "OK to ship".
- T-bar reduced to 11.2 in-oz post Job#1 and then 11.0 in-oz.

11.4 Appendix 4 – Matrices

Matrix 1 – DM with side-effects

	Function	#
1	Provide vehicle directional control (degrees)	1
1.2.1	Transfer strg wheel angular displacement (torque) to angular displacement (torque) at I-shaft	2
1.2.2	Transfer force from strg column to I/P to locate strg column	3
1.2.3	Transfer force from strg wheel to column to locate wheel	4
1.2.4	Allows column shaft rotation	5
1.2.5	Allows variable angular position between column shaft and I-shaft	6
1.3.1	Transfer Torque between Steering Gear and Steering Column	7
1.3.2	Transfer force from I-shaft to gear to locate I-shaft	8
1.3.3	Transfers torque from column to lower I-shaft	9
1.3.4	To fix position of I-shaft with respect to dash (allows rotation)	10
1.3.5	Transfers torque from upper I-shaft to lower I-shaft (155o bend while permitting rotation)	11
1.3.6	Transfers torque from lower I-shaft to upper yolk (U-joint)	12
1.3.7	Transfers torque from lower I-shaft tube to flex coupling	13
1.3.8	Transfers torque from lower I-shaft to lower U-joint	14
1.4.1	Convert I-shaft displacement/torque to displacement/ force at knuckle at a specified ratio & force to frame	15
1.4.2	React force from I-shaft (secondary couple & axial force)	16
1.4.3	React force from knuckle to maintain position of points 12 on knuckle	17
1.4.4	React force from intermediate shaft to locate intermediate shaft	18
1.4.5	Convert angular position of intermediate shaft to axial position of the inner tie rod ball joint.	19
1.4.6	Maintain sealed power steering system	20
1.4.7	Steering gear main structure - connection points	21
1.4.8	Transfer load from gear housing to frame	22
1.4.9	Prevent foreign material from entering gear housing	23
1.4.10	Maintain fixed distance (rack to nuckle) Transfer load	24
1.4.11	Allows swinging arc motion - connects tie rods to rack	25
1.4.12	Provide meshing force between rack and pinion	26
1.4.13	Transfers torsional load from I-shaft to pinion gear	27
1.4.14	Metering of hydraulic flow - power steering boost curve	28
1.5.1	Transfer force from strg wheel to column to locate wheel	29
1.5.2	Transfers torque from driver to shaft - Driver interface to steering system	30
1.6.1	Supports Vehicle Load at specified Ride Height (mm)	31
1.6.2	Transfers Loads / Secures Unsprung mass to Sprung Mass	32
1.6.3	Provide Long., Lat. Damping	33
1.6.4	Provide Vertical damping	34
1.6.5	Supports corner weight	35
1.6.6	Provides roll rate	36
1.6.7	Mechanical link - translates bar rate to lower control arm	37
1.6.8	Allows multi axis motion between upper control arm and wheel-end	38
1.6.9	Allows multi axis motion between lower control arm and wheel-end	39
1.6.10	Secures sta-bar bushing to frame	40
1.6.11	Provides pivot axis for sta bar	41
1.7.1	Provide rolling friction for vehicle control	42
1.7.2	Provide force transfer between tire and ground	43
1.7.3	Provide force transfer between tire and wheel	44
1.7.4	Provide isolation from road input	45
1.7.5	Provide absorbtion and damping from road input	46
1.7.6	Provide force transfer between the tire and wheel	47
1.7.7	Provide force transfer between wheel and hub	48
1.7.8	Joint retention - attachment mechanism for wheel to hub	49
1.8.1	Transmit torque (braking) to wheel	50
1.8.2	Transmit half shaft torque to wheel torque	51
1.8.3	Support front corner weight (loads)	52
1.8.4	Provide rotation	53
1.8.5	Create clamp force to generate braking torque to rotor	54
1.8.6	Supports corner weight, connection to hub, defines distance between upper and lower arms	55
1.8.7	Transfers load from wheel to nuckle - allows rotation about axis	56
1.8.8	Transfer load from nuckle to caliper	57

#	Component (column)
1	Steering system
2	Steering column shaft
3	Column housing assembly
4	column shaft - steering wheel attachment feature
5	Shaft bearings (w/ grease)
6	Column end U-joint
7	I-shaft assembly
8	lower I-shaft U-joint
9	Upper I-shaft (shaft/ tube)
10	Dash seal/ bearing
11	Lower I-shaft upper yolk (U-joint)
12	Flex coupling (disk isolator)
13	Lower I-Shaft
14	Lower I-Shaft Tube
15	Steering gear subsystem
16	Input shaft positioning features
17	Outer tie rod ball studs
18	Input shaft - interface feature
19	rack and pinion
20	rack seals
21	Steering gear housing
22	Steering gear housing bushings
23	Steering gear boots
24	Tie rods
25	Inner tie rod ball studs
26	Yoke Spring
27	T-bar
28	Valve assembly
29	steering wheel attachment feature
30	Steering wheel
31	Suspension system
32	Control arms
33	Bushings
34	Shock absorber
35	Coil over shock module (2)
36	Stabilizer bar
37	Stabilizer bar links (2)
38	Upper ball joint (2)
39	Lower ball joint (2)
40	Stabilizer bar bracket (2)
41	Stabilizer bar bracket bushing (2)
42	Tire/wheel assembly
43	Tire tread
44	Tire bead
45	Tire air cavity
46	Tire side wall
47	Wheel rim (bead seats)
48	Wheel "spider" (mounting structure)
49	Lug nuts
50	rotor
51	hub to half shaft interface feature
52	Wheel end subsystem
53	hub bearing
54	brake caliper assembly
55	Steering Knuckle
56	Hub assembly (hub, bearing, studs)
57	Anchor braket

Matrix 2 – Partitioned DM

FR/DP

FR	Functional Requirement	DP
1	Provide vehicle directional control (degrees)	1
1.2.2	Transfer force from strg column to I/P to locate strg column	3
1.4.7	Steering gear main structure - connection points	21
1.6.5	Supports corner weight	35
1.7.2	Provide force transfer between tire and ground	43
1.2.5	Allows variable angular position between column shaft and I-shaft	6
1.4.6	Maintain sealed power steering system	20
1.4.8	Transfer load from gear housing to frame	22
1.4.2	React force from I-shaft (secondary couple & axial force)	16
1.4.9	Prevent foreign material from entering gear housing	23
1.2.3	Transfer force from strg wheel to column to locate wheel	4
1.5.1	Transfer force from strg wheel to column to locate wheel	29
1.5.2	Transfers torque from driver to shaft - Driver interface to steering system	30
1.7.3	Provide force transfer between tire and wheel	44
1.7.6	Provide force transfer between the tire and wheel	47
1.2.1	Transfer strg wheel angular displacement (torque) to angular displacement (torque) at I-shaft	2
1.2.4	Allows column shaft rotation	5
1.3.1	Transfer Torque between Steering Gear and Steering Column	7
1.3.2	Transfer force from I-shaft to gear to locate I-shaft	8
1.3.3	Transfers torque from column to lower I-shaft	9
1.3.5	Transfers torque from upper I-shaft to lower I-shaft (155o bend while permitting rotation)	11
1.3.6	Transfers torque from lower I-shaft to upper yolk (U-joint)	12
1.3.7	Transfers torque from lower I-shaft tube to flex coupling	13
1.3.8	Transfers torque from lower I-shaft to lower U-joint	14
1.4.4	React force from intermediate shaft to locate intermediate shaft	18
1.4.1	Convert I-shaft displacement/torque to displacement/ force at knuckle at a specified ratio & force to frame	15
1.6.2	Transfers Loads / Secures Unsprung mass to Sprung Mass	32
1.6.3	Provide Long., Lat. Damping	33
1.6.4	Provide Vertical damping	34
1.6.8	Allows multi axis motion between upper control arm and wheel-end	38
1.6.9	Allows melti axis motion between lower control arm and wheel-end	39
1.8.6	Supports corner weight, connection to hub, defines distance between upper and lower arms	55
1.7.5	Provide absorbtion and damping from road input	46
1.7.4	Provide isolation from road input	45
1.7.7	Provide force transfer between wheel and hub	48
1.7.8	Joint retention - attachment mechanism for wheel to hub	49
1.8.1	Transmit torque (braking) to wheel	50
1.8.3	Support front corner weight (loads)	52
1.8.4	Provide rotation	53
1.8.7	Transfers load from wheel to nuckle - allows rotation about axis	56
1.4.3	React force from knuckle to maintain position of points 12 on knuckle	17
1.4.10	Maintain fixed distance (rack to nuckle) Transfer load	24
1.4.11	Allows swinging arc motion - connects tie rods to rack	25
1.4.13	Transfers torsional load from I-shaft to pinion gear	27
1.4.14	Metering of hydraulic flow - power steering boost curve	28
1.6.11	Provides pivot axis for sta bar	41
1.6.6	Provides roll rate	36
1.6.7	Mechanical link - translates bar rate to lower control arm	37
1.4.5	Convert angular position of intermediate shaft to axial position of the inner tie rod ball joint.	19
1.4.12	Provide meshing force between rack and pinion	26
1.7.1	Provide rolling friction for vehicle control	42
1.8.8	Transfer load from nuckle to caliper	57
1.3.4	To fix position of I-shaft with respect to dash (allows rotation)	10
1.6.1	Supports Vehicle Load at specified Ride Height (mm)	31
1.6.10	Secures sta-bar bushing to frame	40
1.8.2	Transmit half shaft torque to wheel torque	51
1.8.5	Create clamp force to generate braking torque to rotor	54

DP	Design Parameter (column)
1	Steering system
3	Column housing assembly
21	Steering gear housing
35	Coil over shock module (2)
43	Tire tread
6	Column end U-joint
20	rack seals
22	Steering gear housing bushings
16	Input shaft positioning features
23	Steering gear boots
4	column shaft - steering wheel attachment feature
29	steering wheel attachment feature
30	Steering wheel
44	Tire bead
47	Wheel rim (bead seats)
2	Steering column shaft
5	Shaft bearings (w/ grease)
7	I-shaft assembly
8	lower I-shaft U-joint
9	Upper I-shaft (shaft/ tube)
11	Lower I-shaft upper yolk (U-joint)
12	Flex coupling (disk isolator)
13	Lower I-Shaft
14	Lower I-Shaft Tube
18	Input shaft - interface feature
15	Steering gear subsystem
32	Control arms
33	Bushings
34	Shock absorber
38	Upper ball joint (2)
39	Lower ball joint (2)
55	Steering Knuckle
46	Tire side wall
45	Tire air cavity
48	Wheel "spider" (mounting structure)
49	Lug nuts
50	rotor
52	Wheel end subsystem
53	hub bearing
56	Hub assembly (hub, bearing, studs)
17	Outer tie rod ball studs
24	Tie rods
25	Inner tie rod ball studs
27	T-bar
28	Valve assembly
41	Stabilizer bar bracket bushing (2)
36	Stabilizer bar
37	Stabilizer bar links (2)
19	rack and pinion
26	Yoke Spring
42	Tire/wheel assembly
57	Anchor braket
10	Dash seal/ bearing
31	Suspension system
40	Stabilizer bar bracket (2)
51	hub to half shaft interface feature
54	brake caliper assembly

Matrix 3 – DSM

			Steering system	Steering column shaft	Column housing assembly	column shaft - steering wheel attachment feature	Shaft bearings (w/ grease)	Column end U-joint	I-shaft assembly	lower I-shaft U-joint	Upper I-shaft (shaft/ tube)	Dash seal/ bearing	Lower I-shaft upper yolk (U-joint)	Flex coupling (disk isolator)	Lower I-Shaft	Lower I-Shaft Tube	Steering gear subsystem	Input shaft positioning features	Outer tie rod ball studs	Input shaft - interface feature	rack and pinion	rack seals	Steering gear housing	Steering gear housing bushings	Steering gear boots	Tie rods	Inner tie rod ball studs	Yoke Spring	T-bar	Valve assembly	steering wheel attachment feature	Steering wheel	Suspension system	Control arms	Bushings	Shock absorber	Coil over shock module (2)	Stabilizer bar	Stabilizer bar links (2)	Upper ball joint (2)	Lower ball joint (2)	Stabilizer bar bracket (2)	Stabilizer bar bracket bushing (2)	Tire/wheel assembly	Tire tread	Tire bead	Tire air cavity	Tire side wall	Wheel rim (bead seats)	Wheel "spider" (mounting structure)	Lug nuts	rotor	hub to half shaft interface feature	Wheel end subsystem	hub bearing	brake caliper assembly	Steering Knuckle	Hub assembly (hub, bearing, studs)	Anchor braket
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
1	Steering system	1	0																																																								
1.2.1	Steering column shaft	2		0		1	1	1																							1	1																									
1.2.2	Column housing assembly	3			0																																																				
1.2.3	column shaft - steering wheel attachment feature	4				0																									1	1																											
1.2.4	Shaft bearings (w/ grease)	5		1			0																																																			
1.2.5	Column end U-joint	6			1			0																																																	
1.3.1	I-shaft assembly	7		1					0								1																																								
1.3.2	lower I-shaft U-joint	8								0						1				1																																					
1.3.3	Upper I-shaft (shaft/ tube)	9					1	1			0		1	1	1																																										
1.3.4	Dash seal/ bearing	10									1	0																																													
1.3.5	Lower I-shaft upper yolk (U-joint)	11									1		0	1	1																																										
1.3.6	Flex coupling (disk isolator)	12											1	0	1																																										
1.3.7	Lower I-Shaft	13													0	1																																									
1.3.8	Lower I-Shaft Tube	14								1					1	0																																									
1.4.1	Steering gear subsystem	15							1								0																							1	1																1		
1.4.2	Input shaft positioning features	16																0					1	1																																	
1.4.3	Outer tie rod ball studs	17																	0							1																															1		
1.4.4	Input shaft - interface feature	18								1							1			0																																					
1.4.5	rack and pinion	19							1											1	0	1					1	1	1																												
1.4.6	rack seals	20																				0	1																																		
1.4.7	Steering gear housing	21																					0																																		
1.4.8	Steering gear housing bushings	22																					1	0																																	
1.4.9	Steering gear boots	23																				1			0																																
1.4.10	Tie rods	24																	1							0	1																														
1.4.11	Inner tie rod ball studs	25																								1	0																														
1.4.12	Yoke Spring	26																			1							0																													
1.4.13	T-bar	27								1								1		1									0	1																											
1.4.14	Valve assembly	28																				1							1	0																											
1.5.1	steering wheel attachment feature	29				1																									0	1																											
1.5.2	Steering wheel	30				1																									1	0																											
1.6.1	Suspension system	31																															0	1			1							1										1					
1.6.2	Control arms	32																																0	1		1			1	1																		
1.6.3	Bushings	33																																	0		1								1			1											
1.6.4	Shock absorber	34																																		0	1										1	1											
1.6.5	Coil over shock module (2)	35																																			0																						
1.6.6	Stabilizer bar	36																																1				0	1				1																
1.6.7	Stabilizer bar links (2)	37																																1				1	0																				
1.6.8	Upper ball joint (2)	38																																1						0	1																1		
1.6.9	Lower ball joint (2)	39																																1						1	0																1		
1.6.10	Stabilizer bar bracket (2)	40																																								0	1																
1.6.11	Stabilizer bar bracket bushing (2)	41																																				1					0																
1.7.1	Tire/wheel assembly	42																																										0	1													1	
1.7.2	Tire tread	43																																											0														
1.7.3	Tire bead	44																																												0			1										
1.7.4	Tire air cavity	45																																	1	1									1		0	1											
1.7.5	Tire side wall	46												1	1	1						1													1	1									1		1	0											
1.7.6	Wheel rim (bead seats)	47																																												1			0										
1.7.7	Wheel "spider" (mounting structure)	48																																																0	1	1						1	
1.7.8	Lug nuts	49																																																1	0	1						1	
1.8.1	rotor	50																																																1	1	0						1	
1.8.2	hub to half shaft interface feature	51																																																1	1	1	0		1			1	
1.8.3	Wheel end subsystem	52																																1			1			1	1						1		1	1				0					
1.8.4	hub bearing	53																																																				1	0			1	
1.8.5	brake caliper assembly	54																																																						0	1		1
1.8.6	Steering Knuckle	55																																1			1			1	1						1		1	1				1			0		
1.8.7	Hub assembly (hub, bearing, studs)	56																																																1					1		1	0	
1.8.8	Anchor braket	57																																																							1		0

Matrix 4 – Spatial interactions only

			Steering system	Steering column shaft	Column housing assembly	column shaft - steering wheel attachment feature	Shaft bearings (w/ grease)	Column end U-joint	I-shaft assembly	lower I-shaft U-joint	Upper I-shaft (shaft/ tube)	Dash seal/ bearing	Lower I-shaft upper yolk (U-joint)	Flex coupling (disk isolator)	Lower I-Shaft	Lower I-Shaft Tube	Steering gear subsystem	Input shaft positioning features	Outer tie rod ball studs	Input shaft - interface feature	rack and pinion	rack seals	Steering gear housing	Steering gear housing bushings	Steering gear boots	Tie rods	Inner tie rod ball studs	Yoke Spring	T-bar	Valve assembly	steering wheel attachment feature	Steering wheel	Suspension system	Control arms	Bushings	Shock absorber	Coil over shock module (2)	Stabilizer bar	Stabilizer bar links (2)	Upper ball joint (2)	Lower ball joint (2)	Stabilizer bar bracket (2)	Stabilizer bar bracket bushing (2)	Tire/wheel assembly	Tire tread	Tire bead	Tire air cavity	Tire side wall	Wheel rim (bead seats)	Wheel "spider" (mounting structure)	Lug nuts	rotor	hub to half shaft interface feature	Wheel end subsystem	hub bearing	brake caliper assembly	Steering Knuckle	Hub assembly (hub, bearing, studs)	Anchor braket
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
1	Steering system	1	0																																																									
1.2.1	Steering column shaft	2		0		1	1	1	1																																																		
1.2.2	Column housing assembly	3			0		1																																																				
1.2.3	column shaft - steering wheel attachment feature	4		1		0																									1																												
1.2.4	Shaft bearings (w/ grease)	5		1	1		0																																																				
1.2.5	Column end U-joint	6		1				0			1																																																
1.3.1	I-shaft assembly	7		1					0								1																																										
1.3.2	lower I-shaft U-joint	8								0						1				1																																							
1.3.3	Upper I-shaft (shaft/ tube)	9						1			0	1	1																																														
1.3.4	Dash seal/ bearing	10									1	0																																															
1.3.5	Lower I-shaft upper yolk (U-joint)	11									1		0	1																																													
1.3.6	Flex coupling (disk isolator)	12											1	0	1																																												
1.3.7	Lower I-Shaft	13												1	0	1																																											
1.3.8	Lower I-Shaft Tube	14								1					1	0																																											
1.4.1	Steering gear subsystem	15							1								0																																				1					
1.4.2	Input shaft positioning features	16																0		1			1																																				
1.4.3	Outer tie rod ball studs	17																	0							1																															1		
1.4.4	Input shaft - interface feature	18								1								1		0									1	1																													
1.4.5	rack and pinion	19																			0	1					1	1	1	1																													
1.4.6	rack seals	20																			1	0	1																																				
1.4.7	Steering gear housing	21																1				1	0	1	1			1																															
1.4.8	Steering gear housing bushings	22																					1	0																																			
1.4.9	Steering gear boots	23																					1		0	1																																	
1.4.10	Tie rods	24																	1						1	0	1																																
1.4.11	Inner tie rod ball studs	25																			1					1	0																																
1.4.12	Yoke Spring	26																			1		1					0																															
1.4.13	T-bar	27																		1	1								0																														
1.4.14	Valve assembly	28																		1	1									0																													
1.5.1	steering wheel attachment feature	29				1																									0	1																											
1.5.2	Steering wheel	30																													1	0																											
1.6.1	Suspension system	31																															0																					1					
1.6.2	Control arms	32																																0	1		1		1	1	1																		
1.6.3	Bushings	33																																1	0																								
1.6.4	Shock absorber	34																																		0																							
1.6.5	Coil over shock module (2)	35																																1			0																						
1.6.6	Stabilizer bar	36																																				0	1				1																
1.6.7	Stabilizer bar links (2)	37																																1				1	0																				
1.6.8	Upper ball joint (2)	38																																1						0																	1		
1.6.9	Lower ball joint (2)	39																																1							0																1		
1.6.10	Stabilizer bar bracket (2)	40																																								0	1																
1.6.11	Stabilizer bar bracket bushing (2)	41																																				1				1	0																
1.7.1	Tire/wheel assembly	42																																										0										1					
1.7.2	Tire tread	43																																											0		1	1											
1.7.3	Tire bead	44																																												0		1	1										
1.7.4	Tire air cavity	45																																											1		0	1											
1.7.5	Tire side wall	46																																											1	1	1	0											
1.7.6	Wheel rim (bead seats)	47																																												1			0	1									
1.7.7	Wheel "spider" (mounting structure)	48																																															1	0	1	1							
1.7.8	Lug nuts	49																																																1	0							1	
1.8.1	rotor	50																																																1		0						1	
1.8.2	hub to half shaft interface feature	51																																																			0					1	
1.8.3	Wheel end subsystem	52															1																1											1										0					
1.8.4	hub bearing	53																																																					0			1	
1.8.5	brake caliper assembly	54																																																						0			1
1.8.6	Steering Knuckle	55																	1																					1	1																0	1	1
1.8.7	Hub assembly (hub, bearing, studs)	56																																																	1	1	1		1		1	0	
1.8.8	Anchor braket	57																																																						1	1		0

Matrix 5 – side-effects + spatial interactions

			Steering system	Steering column shaft	Column housing assembly	column shaft - steering wheel attachm	Shaft bearings (w/ grease)	Column end U-joint	I-shaft assembly	lower I-shaft U-joint	Upper I-shaft (shaft/ tube)	Dash seal/ bearing	Lower I-shaft upper yolk (U-joint)	Flex coupling (disk isolator)	Lower I-Shaft	Lower I-Shaft Tube	Steering gear subsystem	Input shaft positioning features	Outer tie rod ball studs	Input shaft - interface feature	rack and pinion	rack seals	Steering gear housing	Steering gear housing bushings	Steering gear boots	Tie rods	Inner tie rod ball studs	Yoke Spring	T-bar	Valve assembly	steering wheel attachment feature	Steering wheel	Suspension system	Control arms	Bushings	Shock absorber	Coil over shock module (2)	Stabilizer bar	Stabilizer bar links (2)	Upper ball joint (2)	Lower ball joint (2)	Stabilizer bar bracket (2)	Stabilizer bar bracket bushing (2)	Tire/wheel assembly	Tire tread	Tire bead	Tire air cavity	Tire side wall	Wheel rim (bead seats)	Wheel "spider" (mounting structure)	Lug nuts	rotor	hub to half shaft interface feature	Wheel end subsystem	hub bearing	brake caliper assembly	Steering Knuckle	Hub assembly (hub, bearing, studs)	Anchor braket
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
1	Steerihg system	1	3																																																								
1.2.1	Steering column shaft	2		3		3	3	3	2																						1	1																											
1.2.2	Column housing assembly	3			3		2																																																				
1.2.3	column shaft - steering wheel attachment feature	4		2		3																									3	1																											
1.2.4	Shaft bearings (w/ grease)	5		3	2		3																																																				
1.2.5	Column end U-joint	6		2	1			3			2																																																
1.3.1	I-shaft assembly	7		3					3								3																																										
1.3.2	lower I-shaft U-joint	8								3						3				3																																							
1.3.3	Upper I-shaft (shaft/ tube)	9					1	3			3	2	3	1	1																																												
1.3.4	Dash seal/ bearing	10									3	3																																															
1.3.5	Lower I-shaft upper yolk (U-joint)	11									3		3	3	1																																												
1.3.6	Flex coupling (disk isolator)	12											3	3	3																																												
1.3.7	Lower I-Shaft	13												2	3	3																																											
1.3.8	Lower I-Shaft Tube	14								3					3	3																																											
1.4.1	Steering gear subsystem	15							3								3																							1	1													2			1		
1.4.2	Input shaft positioning features	16																3		2			3	1																																			
1.4.3	Outer tie rod ball studs	17																	3							3																															3		
1.4.4	Input shaft - interface feature	18								3							1	2		3									2	2																													
1.4.5	rack and pinion	19							1											1	3	3					3	3	3	2																													
1.4.6	rack seals	20																			2	3	3																																				
1.4.7	Steering gear housing	21																2				2	3	2	2			2																															
1.4.8	Steering gear housing bushings	22																					3	3																																			
1.4.9	Steering gear boots	23																				1	2		3	2																																	
1.4.10	Tie rods	24																	3						2	3	3																																
1.4.11	Inner tie rod ball studs	25																			2					3	3																																
1.4.12	Yoke Spring	26																			3		2					3																															
1.4.13	T-bar	27								1								1		3	2								3	1																													
1.4.14	Valve assembly	28																		2	2	1							1	3																													
1.5.1	steering wheel attachment feature	29				3																									3	3																											
1.5.2	Steering wheel	30				1																									3	3																											
1.6.1	Suspension system	31																															3	1			1							1										3					
1.6.2	Control arms	32																																3	3		3		2	3	3																		
1.6.3	Bushings	33																																2	3		1								1			1											
1.6.4	Shock absorber	34																																		3	1										1	1											
1.6.5	Coil over shock module (2)	35																																2			3																						
1.6.6	Stabilizer bar	36																																1				3	3				3																
1.6.7	Stabilizer bar links (2)	37																																3				3	3																				
1.6.8	Upper ball joint (2)	38																																3						3	1																3		
1.6.9	Lower ball joint (2)	39																																3						1	3																3		
1.6.10	Stabilizer bar bracket (2)	40																																								3	3																
1.6.11	Stabilizer bar bracket bushing (2)	41																																				3				2	3																
1.7.1	Tire/wheel assembly	42																																										3	1									2				1	
1.7.2	Tire tread	43																																											3		2	2											
1.7.3	Tire bead	44																																												3		2	3										
1.7.4	Tire air cavity	45																																	1	1									3		3	3											
1.7.5	Tire side wall	46												1	1	1						1													1	1									3	2	3	3											
1.7.6	Wheel rim (bead seats)	47																																												3			3	2									
1.7.7	Wheel "spider" (mounting structure)	48																																															2	3	3	3						1	
1.7.8	Lug nuts	49																																																3	3	1						3	
1.8.1	rotor	50																																																3	1	3						3	
1.8.2	hub to half shaft interface feature	51																																																1	1	1	3		1			3	
1.8.3	Wheel end subsystem	52															2																2	1			1			1	1			2			1		1	1				3					
1.8.4	hub bearing	53																																																				1	3			3	
1.8.5	brake caliper assembly	54																																																						3	1		3
1.8.6	Steering Knuckle	55																	2															1			1			3	3						1		1	1				1			3	2	2
1.8.7	Hub assembly (hub, bearing, studs)	56																																																1	2	2	2		3		3	3	
1.8.8	Anchor braket	57																																																						2	3		3

Matrix 6 – Nibble relationships only

				1 Steering system	2 Steering column shaft	3 Column housing assembly	4 column shaft - steering wheel attachment feature	5 Shaft bearings (w/ grease)	6 Column end U-joint	7 I-shaft assembly	8 lower I-shaft U-joint	9 Upper I-shaft (shaft/ tube)	10 Dash seal/ bearing	11 Lower I-shaft upper yolk (U-joint)	12 Flex coupling (disk isolator)	13 Lower I-Shaft	14 Lower I-Shaft Tube	15 Steering gear subsystem	16 Input shaft positioning features	17 Outer tie rod ball studs	18 Input shaft - interface feature	19 rack and pinion	20 rack seals	21 Steering gear housing	22 Steering gear housing bushings	23 Steering gear boots	24 Tie rods	25 Inner tie rod ball studs	26 Yoke Spring	27 T-bar	28 Valve assembly	29 steering wheel attachment feature	30 Steering wheel	31 Suspension system	32 Control arms	33 Bushings	34 Shock absorber	35 Coil over shock module (2)	36 Stabilizer bar	37 Stabilizer bar links (2)	38 Upper ball joint (2)	39 Lower ball joint (2)	40 Stabilizer bar bracket (2)	41 Stabilizer bar bracket bushing (2)	42 Tire/wheel assembly	43 Tire tread	44 Tire bead	45 Tire air cavity	46 Tire side wall	47 Wheel rim (bead seats)	48 Wheel "spider" (mounting structure)	49 Lug nuts	50 rotor	51 hub to half shaft interface feature	52 Wheel end subsystem	53 hub bearing	54 brake caliper assembly	55 Steering Knuckle	56 Hub assembly (hub, bearing, studs)	57 Anchor braket
1	Steering system		1	0																																																								
1.2.1	Steering column shaft	N	2		0						1										1	1	1	1				1	1	1	1			1		1	1									1	1			1	1								1	1	
1.2.2	Column housing assembly		3			0																																																					
1.2.3	column shaft - steering wheel attachment feature		4				0																																																				
1.2.4	Shaft bearings (w/ grease)		5					0																																																			
1.2.5	Column end U-joint		6						0																																																		
1.3.1	I-shaft assembly	N	7		1					0										1	1	1	1				1	1	1	1			1		1	1									1	1			1	1								1	1	
1.3.2	lower I-shaft U-joint		8								0																																																
1.3.3	Upper I-shaft (shaft/ tube)		9									0																																															
1.3.4	Dash seal/ bearing		10										0																																														
1.3.5	Lower I-shaft upper yolk (U-joint)		11											0																																													
1.3.6	Flex coupling (disk isolator)		12												0																																												
1.3.7	Lower I-Shaft		13													0																																											
1.3.8	Lower I-Shaft Tube		14														0																																										
1.4.1	Steering gear subsystem		15															0																																									
1.4.2	Input shaft positioning features		16																0																																								
1.4.3	Outer tie rod ball studs	N	17		1					1										0	1	1	1				1	1	1	1			1		1	1									1	1			1	1								1	1	
1.4.4	Input shaft - interface feature	N	18		1					1										1	0	1	1				1	1	1	1			1		1	1									1	1			1	1								1	1	
1.4.5	rack and pinion	N	19		1					1										1	1	0	1				1	1	1	1			1		1	1									1	1			1	1								1	1	
1.4.6	rack seals	N	20		1					1										1	1	1	0				1	1	1	1			1		1	1									1	1			1	1								1	1	
1.4.7	Steering gear housing		21																					0																																			
1.4.8	Steering gear housing bushings		22																						0																																		
1.4.9	Steering gear boots		23																							0																																	
1.4.10	Tie rods	N	24		1					1										1	1	1	1				0	1	1	1			1		1	1									1	1			1	1								1	1	
1.4.11	Inner tie rod ball studs	N	25		1					1										1	1	1	1				1	0	1	1			1		1	1									1	1			1	1								1	1	
1.4.12	Yoke Spring	N	26		1					1										1	1	1	1				1	1	0	1			1		1	1									1	1			1	1								1	1	
1.4.13	T-bar	N	27		1					1										1	1	1	1				1	1	1	0			1		1	1									1	1			1	1								1	1	
1.4.14	Valve assembly		28																												0																												
1.5.1	steering wheel attachment feature		29																													0																											
1.5.2	Steering wheel	N	30		1					1										1	1	1	1				1	1	1	1			0		1	1									1	1			1	1								1	1	
1.6.1	Suspension system		31																															0																									
1.6.2	Control arms	N	32		1					1										1	1	1	1				1	1	1	1			1		0	1									1	1			1	1								1	1	
1.6.3	Bushings	N	33		1					1										1	1	1	1				1	1	1	1			1		1	0									1	1			1	1								1	1	
1.6.4	Shock absorber		34																																		0																						
1.6.5	Coil over shock module (2)		35																																			0																					
1.6.6	Stabilizer bar		36																																				0																				
1.6.7	Stabilizer bar links (2)		37																																					0																			
1.6.8	Upper ball joint (2)		38																																						0																		
1.6.9	Lower ball joint (2)		39																																							0																	
1.6.10	Stabilizer bar bracket (2)		40																																								0																
1.6.11	Stabilizer bar bracket bushing (2)		41																																									0															
1.7.1	Tire/wheel assembly	N	42		1					1										1	1	1	1				1	1	1	1			1		1	1									0	1			1	1								1	1	
1.7.2	Tire tread	N	43		1					1										1	1	1	1				1	1	1	1			1		1	1									1	0			1	1								1	1	
1.7.3	Tire bead		44																																												0												
1.7.4	Tire air cavity		45																																													0											
1.7.5	Tire side wall	N	46		1					1										1	1	1	1				1	1	1	1			1		1	1									1	1			0	1								1	1	
1.7.6	Wheel rim (bead seats)	N	47		1					1										1	1	1	1				1	1	1	1			1		1	1									1	1			1	0								1	1	
1.7.7	Wheel "spider" (mounting structure)		48																																																0								
1.7.8	Lug nuts		49																																																	0							
1.8.1	rotor		50																																																		0						
1.8.2	hub to half shaft interface feature		51																																																			0					
1.8.3	Wheel end subsystem		52																																																				0				
1.8.4	hub bearing		53																																																					0			
1.8.5	brake caliper assembly		54																																																						0		
1.8.6	Steering Knuckle	N	55		1					1										1	1	1	1				1	1	1	1			1		1	1									1	1			1	1								0	1	
1.8.7	Hub assembly (hub, bearing, studs)	N	56		1					1										1	1	1	1				1	1	1	1			1		1	1									1	1			1	1								1	0	
1.8.8	Anchor braket		57																																																									0

Matrix 7 – Nibble + spatial + side-effects

				Steering system	Steering column shaft	Column housing assembly	column shaft - steering wheel attachment feature	Shaft bearings (w/ grease)	Column end U-joint	I-shaft assembly	lower I-shaft U-joint	Upper I-shaft (shaft/ tube)	Dash seal/ bearing	Lower I-shaft upper yolk (U-joint)	Flex coupling (disk isolator)	Lower I-Shaft	Lower I-Shaft Tube	Steering gear subsystem	Input shaft positioning features	Outer tie rod ball studs	Input shaft - interface feature	rack and pinion	rack seals	Steering gear housing	Steering gear housing bushings	Steering gear boots	Tie rods	Inner tie rod ball studs	Yoke Spring	T-bar	Valve assembly	steering wheel attachment feature	Steering wheel	Suspension system	Control arms	Bushings	Shock absorber	Coil over shock module (2)	Stabilizer bar	Stabilizer bar links (2)	Upper ball joint (2)	Lower ball joint (2)	Stabilizer bar bracket (2)	Stabilizer bar bracket bushing (2)	Tire/wheel assembly	Tire tread	Tire bead	Tire air cavity	Tire side wall	Wheel rim (bead seats)	Wheel "spider" (mounting structure)	Lug nuts	rotor	hub to half shaft interface feature	Wheel end subsystem	hub bearing	brake caliper assembly	Steering Knuckle	Hub assembly (hub, bearing, studs)	Anchor braket
					N					N											N	N	N	N				N	N	N	N			N		N	N										N	N			N	N									N	N	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
1	Steering system		1	3																																																								
1.2.1	Steering column shaft	N	2		3		2	2	2	3																						2	3																										
1.2.2	Column housing assembly		3			3		2																																																			
1.2.3	column shaft - steering wheel attachment feature		4		2		3																									2	2																										
1.2.4	Shaft bearings (w/ grease)		5		2	2		3																																																				
1.2.5	Column end U-joint		6		2	2			3			2																																															
1.3.1	I-shaft assembly	N	7		3					3								2																																									
1.3.2	lower I-shaft U-joint		8								3						2				2																																						
1.3.3	Upper I-shaft (shaft/ tube)		9					2	2			3	2	2	2	2																																											
1.3.4	Dash seal/ bearing		10									2	3																																														
1.3.5	Lower I-shaft upper yolk (U-joint)		11									2		3	2	2																																											
1.3.6	Flex coupling (disk isolator)		12											2	3	2																																											
1.3.7	Lower I-Shaft		13												2	3	2																																										
1.3.8	Lower I-Shaft Tube		14								2					2	3																																											
1.4.1	Steering gear subsystem		15							2									3																							2	2														2			2		
1.4.2	Input shaft positioning features		16																		3		2			2	2																																			
1.4.3	Outer tie rod ball studs	N	17																			3							3																																3		
1.4.4	Input shaft - interface feature	N	18								2							2	2		3											3	2																														
1.4.5	rack and pinion	N	19							3													3	3	3					3	3	3	2																														
1.4.6	rack seals	N	20																				3	3	2																																					
1.4.7	Steering gear housing		21																2				2	3	2	2			2																																
1.4.8	Steering gear housing bushings		22																						2	3																																				
1.4.9	Steering gear boots		23																					2	2		3	2																																		
1.4.10	Tie rods	N	24																	3								2	3	3																																
1.4.11	Inner tie rod ball studs	N	25																			3						3	3																																		
1.4.12	Yoke Spring	N	26																			3			2					3																																
1.4.13	T-bar	N	27								2								2		3	3								3	2																														
1.4.14	Valve assembly		28																		2	2	2							2	3																														
1.5.1	steering wheel attachment feature		29				2																									3	2																										
1.5.2	Steering wheel	N	30				2																									2	3																										
1.6.1	Suspension system		31																														3	2			2								2											2					
1.6.2	Control arms	N	32																															3	3		2		2	2	2																		
1.6.3	Bushings	N	33																															3	3		2								3			3											
1.6.4	Shock absorber		34																																		3	2										2	2												
1.6.5	Coil over shock module (2)		35																															2			3																							
1.6.6	Stabilizer bar		36																															2				3	2				2																
1.6.7	Stabilizer bar links (2)		37																															2				2	3																				
1.6.8	Upper ball joint (2)		38																															2						3	2																	2		
1.6.9	Lower ball joint (2)		39																															2						2	3																	2		
1.6.10	Stabilizer bar bracket (2)		40																																								3	2															
1.6.11	Stabilizer bar bracket bushing (2)		41																																				2				2	3															
1.7.1	Tire/wheel assembly	N	42																																										3	3									2				3	
1.7.2	Tire tread	N	43																																											3		2	3												
1.7.3	Tire bead		44																																												3		2	2											
1.7.4	Tire air cavity		45																																2	2									2		3	2												
1.7.5	Tire side wall	N	46												2	2	2						3													3	2									3	2	2	3											
1.7.6	Wheel rim (bead seats)	N	47																																												2			3	2									
1.7.7	Wheel "spider" (mounting structure)		48																																															2	3	2	2						2	
1.7.8	Lug nuts		49																																																2	3	2						2	
1.8.1	rotor		50																																																2	2	3						2	
1.8.2	hub to half shaft interface feature		51																																																2	2	2	3		2			2	
1.8.3	Wheel end subsystem		52															2																2	2			2			2	2				2			2		2	2				3					
1.8.4	hub bearing		53																																																				2	3			2	
1.8.5	brake caliper assembly		54																																																							3	2		2
1.8.6	Steering Knuckle	N	55																	3																3			2			2	2							2		3	2						2			3	3	2
1.8.7	Hub assembly (hub, bearing, studs)	N	56																																																2	2	2	2		2		3	3	
1.8.8	Anchor braket		57																																																							2	2		3

Matrix 8 – Partitioned Matrix 7

1	Steering system		1
1.2.1	Steering column shaft	N	2
1.2.2	Column housing assembly		3
1.2.3	column shaft - steering wheel attachment feature		4
1.2.4	Shaft bearings (w/ grease)		5
1.2.5	Column end U-joint		6
1.3.1	I-shaft assembly	N	7
1.3.2	lower I-shaft U-joint		8
1.3.3	Upper I-shaft (shaft/ tube)		9
1.3.4	Dash seal/ bearing		10
1.3.5	Lower I-shaft upper yolk (U-joint)		11
1.3.6	Flex coupling (disk isolator)		12
1.3.7	Lower I-Shaft		13
1.3.8	Lower I-Shaft Tube		14
1.4.1	Steering gear subsystem		15
1.4.2	Input shaft positioning features		16
1.4.3	Outer tie rod ball studs	N	17
1.4.4	Input shaft - interface feature	N	18
1.4.5	rack and pinion	N	19
1.4.6	rack seals	N	20
1.4.7	Steering gear housing		21
1.4.8	Steering gear housing bushings		22
1.4.9	Steering gear boots		23
1.4.10	Tie rods	N	24
1.4.11	Inner tie rod ball studs	N	25
1.4.12	Yoke Spring	N	26
1.4.13	T-bar	N	27
1.8.6 ·	Steering Knuckle	N	55
1.5.1	steering wheel attachment feature		29
1.5.2	Steering wheel	N	30
1.6.2	Control arms	N	32
1.7.5	Tire side wall	N	46
1.6.3	Bushings	N	33
1.7.6	Wheel rim (bead seats)	N	47
1.7.1	Tire/wheel assembly	N	42
1.7.2	Tire tread	N	43
1.8.7	Hub assembly (hub, bearing, studs)	N	56
1.4.14	Valve assembly		28
1.6.1	Suspension system		31
1.6.4	Shock absorber		34
1.6.5	Coil over shock module (2)		35
1.6.6	Stabilizer bar		36
1.6.7	Stabilizer bar links (2)		37
1.6.8	Upper ball joint (2)		38
1.6.9	Lower ball joint (2)		39
1.6.10	Stabilizer bar bracket (2)		40
1.6.11	Stabilizer bar bracket bushing (2)		41
1.7.3	Tire bead		44
1.7.4	Tire air cavity		45
1.8.3	Wheel end subsystem		52
1.7.7	Wheel "spider" (mounting structure)		48
1.7.8	Lug nuts		49
1.8.1	rotor		50
1.8.2	hub to half shaft interface feature		51
1.8.4	hub bearing		53
1.8.5	brake caliper assembly		54
1.8.8	Anchor braket		57

Steering system	Steering column shaft	Column housing assembly	column shaft - steering wheel attachment feature	Shaft bearings (w/ grease)	Column end U-joint	I-shaft assembly	lower I-shaft U-joint	Upper I-shaft (shaft/ tube)	Dash seal/ bearing	Lower I-shaft upper yolk (U-joint)	Flex coupling (disk isolator)	Lower I-Shaft	Lower I-Shaft Tube	Steering gear subsystem	Input shaft positioning features	Outer tie rod ball studs	Input shaft - interface feature	rack and pinion	rack seals	Steering gear housing	Steering gear housing bushings	Steering gear boots	Tie rods	Inner tie rod ball studs	Yoke Spring	T-bar	Steering Knuckle	steering wheel attachment feature	Steering wheel	Control arms	Tire side wall	Bushings	Wheel rim (bead seats)	Tire/wheel assembly	Tire tread	Hub assembly (hub, bearing, studs)	Valve assembly	Suspension system	Shock absorber	Coil over shock module (2)	Stabilizer bar	Stabilizer bar links (2)	Upper ball joint (2)	Lower ball joint (2)	Stabilizer bar bracket (2)	Stabilizer bar bracket bushing (2)	Tire bead	Tire air cavity	Wheel end subsystem	Wheel "spider" (mounting structure)	Lug nuts	rotor	hub to half shaft interface feature	hub bearing	brake caliper assembly	Anchor braket
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	55	29	30	32	46	33	47	42	43	56	28	31	34	35	36	37	38	39	40	41	44	45	52	48	49	50	51	53	54	57

Matrix 9 – Manually adjusted Matrix 8

1	Steering system		1
1.2.2	Column housing assembly		3
1.2.3	column shaft - steering wheel attachment feature		4
1.2.4	Shaft bearings (w/ grease)		5
1.2.5	Column end U-joint		6
1.3.2	lower I-shaft U-joint		8
1.5.1	steering wheel attachment feature		29
1.3.3	Upper I-shaft (shaft/ tube)		9
1.3.4	Dash seal/ bearing		10
1.3.5	Lower I-shaft upper yolk (U-joint)		11
1.3.6	Flex coupling (disk isolator)		12
1.3.7	Lower I-Shaft		13
1.4.7	Steering gear housing		21
1.4.8	Steering gear housing bushings		22
1.4.9	Steering gear boots		23
1.3.8	Lower I-Shaft Tube		14
1.4.1	Steering gear subsystem		15
1.4.2	Input shaft positioning features		16
1.2.1	Steering column shaft	N	2
1.3.1	I-shaft assembly	N	7
1.4.3	Outer tie rod ball studs	N	17
1.4.4	Input shaft - interface feature	N	18
1.4.5	rack and pinion	N	19
1.4.6	rack seals	N	20
1.4.10	Tie rods	N	24
1.4.11	Inner tie rod ball studs	N	25
1.4.12	Yoke Spring	N	26
1.4.13	T-bar	N	27
1.8.6	Steering Knuckle	N	55
1.5.2	Steering wheel	N	30
1.6.2	Control arms	N	32
1.7.5	Tire side wall	N	46
1.6.3	Bushings	N	33
1.7.6	Wheel rim (bead seats)	N	47
1.7.1	Tire/wheel assembly	N	42
1.7.2	Tire tread	N	43
1.8.7	Hub assembly (hub, bearing, studs)	N	56
1.4.14	Valve assembly		28
1.6.1	Suspension system		31
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1.6.5	Coil over shock module (2)		35
1.6.6	Stabilizer bar		36
1.6.7	Stabilizer bar links (2)		37
1.6.8	Upper ball joint (2)		38
1.6.9	Lower ball joint (2)		39
1.6.10	Stabilizer bar bracket (2)		40
1.6.11	Stabilizer bar bracket bushing (2)		41
1.7.3	Tire bead		44
1.7.4	Tire air cavity		45
1.8.3	Wheel end subsystem		52
1.7.7	Wheel "spider" (mounting structure)		48
1.7.8	Lug nuts		49
1.8.1	rotor		50
1.8.2	hub to half shaft interface feature		51
1.8.4	hub bearing		53
1.8.5	brake caliper assembly		54
1.8.8	Anchor braket		57

11.5 Appendix 5 – Steering System Constraint

This is the list of requirements sorted by subsystem and catagorized as constraint or FR. If constraint, type of constaint is indicated.

	P-Diagram	P-diagram ideal functional output	Constraint / Function	Type of constraint	Form that provides function
3	Front Suspension	Provide Target Suspension Travels	C	input	Shock module
4	Front Suspension	Provide Target Kinematics thru Wheel travel (tbd deg/m) (tow, caster, camber)	C	input	Control arms, nuckle, gear, frame
5	Front Suspension	Long., Lat., Vert., Toe, Caster, Camber Compliances (deg)	C	input	Control arms, nuckle, bushings, frame
6	Front Suspension	Provide Target Ride Frequency, Wheel Rate, & Roll Stiffness	C	input	Springs, Stabilizer bar
8	Front Suspension	Provide Target Ride and Steering Friction	C	input	Ball joints, shock module
9	Front Suspension	Operates Quietly w/o Squeak & Rattle (< tbd db)	C	input	everything
10	Front Suspension	Meets Modal Targets (Hop, Tramp, Fore-Aft natural frequecy)	C	input	everything
12	Front Suspension	Meets Assembly/Serviceability Requirements	C	input	everything
13	Front Suspension	Meets Recyclability Requirements	C	input	everything
14	Front Suspension	Meets Program Corporate Requirements for Appearance	C	input	everything
15	Front Suspension	Maintains Operating Clearances	C	system	everything
16	Front Suspension	Meets Transportation and Shipping Requirements	C	input	everything
17	Tires	Support static load at specified ride height	C	input	Tire + air pressure
22	Tires	Attractive to customer	C	input	tire side wall and tread
23	Tires	Meets all government regulations	C	input	tire
24	Tires	Meets tire life target	C	input	tire
25	Wheel	Support the static load at specified ride height	C	input	wheel
28	Wheel	Roll true and smooth	C	system	wheel (runnout)
29	Wheel	Serviceability	C	input	wheel
30	Wheel	Attractive to customer (appearance & perception)	C	input	wheel (design)
31	Wheel	Assist in brake cooling	C	system	wheel (window openings)
32	Wheel	Provide attachment capability to ornament	C	system	wheel (ornament attachment features)
33	Wheel	Provide attachment capability to wheel weight	C	system	wheel (flanges)
34	Wheel	Provide attachment capability to valve stem	C	system	wheel (valve hole geometry)
35	Wheel	Provide attachment capability to TPMS	C	system	wheel (drop well geometry)
36	Wheel	Meet all government regulations	C	input	wheel
38	I-shaft	Transmit torque uniformly and on-center within 5% variability	C	input	intermediate shaft assembly (upper shaft, lower shaft, u-joints, flex coupling)
39	I-shaft	Isolate NVH	C	system	flex coupling, dash seal
40	I-shaft	Provide collapse for crash	C	system	Upper and lower I-shafts
41	I-shaft	Ensure assembly and service in correct orientation	C	system	intermediate shaft assembly (upper shaft, lower shaft, u-joints, flex coupling)
42	I-shaft	Seal passenger compartment from engine compartment	C	system	dash seal
44	Rotor	Disipate Heat	C	system	rotor, hub assembly
47	Hub/bearing	Maintain wheel alignment to nuckle	C	input	hub
59	column	23 Seal dash opening	C		Dash seal
60	column	26 Dampen noise from strg gear from going to driver	C		flex coupling
61	column	29 Dampen torque from strg gear from going to strg wheel	C		flex coupling
65	steering gear	Allow knuckle to return to center without assist	C		ball joints
69	steering gear	Meet program appearance requirements	C		steering gear system
70	steering gear	Permit assembly at production rates	C		steering gear system
71	steering gear	Permit service of components	C		steering gear system